CS 111

Contents

Part A.

Preface

Preface: Legend

> **_Operating Systems, Three Easy Pieces_**
>
> Text in these boxes will indicate that further details can be found in the textbook (*Operating Systems: Three Easy Pieces* by Arpaci-Dusseau)

> **Definitions**
>
> Any definitions will be appear in a grey box like this one. There may be more than one definition per box if the topics are dependent on each other or are closely related.

> **Examples**
>
> Any examples will be appear in a blue box like this one. Examples will typically showcase a scenario that emphasizes the importance of a particular topic.

> **Abstractions**
>
> Layers of abstractions will appear in a violet box like this one. The key point of this box is to actively reinforce the concept of abstraction (and recognize how important it is in computer science!).

> **Asides**
>
> Asides will appear in an orange box like this one. Asides usually offer supplemental explanations for more complex topics.

> **Corollaries**
>
> Corollaries will appear in a teal box like this one. Corollaries typically consist of an extension of a topic that is too small for its own section.

Preface: Introduction to Abstraction

> **Definition: Abstraction**
>
> **Abstraction** is the concept of providing a (relatively) simple interface to higher level programs, hiding unnecessary complexity.

The OS implements these abstract resources using physical resources, and thus is the source of one of the main dilemmas of OS design: What should you abstract?

> **Example: Network Neverland**
>
> Network cards consist of intricate technical details and specifications, but most users don't care about them. As a result, the operating system abstracts the technical aspects of a specific network card, such as the process of sending a message, for higher-level programs. Instead of manually performing each step to send a message using a particular network card, users can simply call the OS's `send()`[a] function and let the operating system handle the complex operations.
>
> ─────────────────────────
> [a]The actual function name may vary.

Why Abstract?

Abstraction is utilized to simplify code development and comprehension for programmers and users. Furthermore, it naturally fosters a highly modular codebase as each abstraction introduces an additional layer of modularity. Moreover, by concealing complexity at each layer of abstraction, it encourages programmers to concentrate on the essential functionality of a component.

Due to variability of a machine's hardware and software, we can abstract the common functionality and make different types appear the same. This way, applications only need to interface with a common library.

Chapter 1

Overview

This section defines what an operating system is as well as gives motivating reasons as to why we should be studying them.

1.1 What is an Operating System?

Definition: Operating System

An **operating system (OS)** is system software that acts as an intermediary between hardware and higher level applications (e.g. higher level system software, user processes), acting as an intermediary between the two. It manages hardware and software resources and provides common services for user programs.

Abstraction: The Operating System

The operating system plays a crucial role in managing hardware resources for programs, ensuring controlled sharing, privacy, and overseeing their execution. Moreover, it provides a layer of abstraction that enhances software portability.

1.2 Why Study Them?

We study operating systems because we rely on the *services* they offer.

Definition: Services

In the context of operating systems, **services** are functionality that is provided for by the operating system. They can be accessed via the operating system's API in the form of system calls.

Moreover, a lot of hard problems that we run into at the application layer have (probably) already been solved in the context of operating systems !

Example: Difficult Downloads

Suppose you are developing a web browser and implementing a *download* feature. While downloading things one by one works fine, what if you need to download multiple items from different sites simultaneously? Thinking abstractly, we can see that this is a problem of coordinating concurrent activities, and fortunately, this problem has already been solved in the context of operating systems! Since you have already learned how to tackle this issue in operating systems, now you can apply the same solution to your *download* problem!

1.3 Key Topics (OS Wisdom)

When thinking of how to solve complex problems, these are some things you should take into consideration (to hopefully make your life a lot easier).

Objects and Operations

Think of a service as an object with a set of well-defined operations. Moreover, thinking of the underlying data structure(s) of an object may be useful in many situations.

Interface v. Implementation

> **Definition: Interface and Implementation**
>
> An **interface** defines the collection of functionalities offered by your software. It specifies the method names, signatures, and the *purpose* of each component.
>
> -
>
> An **implementation** refers to the actual code that provides the functionality described by the interface. It specifies *how* the interface's operations are executed and realized in practice.

We separate the two components to improve modularity and create robust, well-structured code. It allows for different compliant implementations (as long as they adhere to the agreed-upon interface specifications). This provides immense flexibility at the implementation level!

> **Example: Sort Swapping**
>
> Assume you are writing a library that contains a collection of common algorithms, one of them being `sort()`. Being the genius that you are, your implementation is as follows: Randomly reorder the elements until they're sorted. By some miracle, your library garners a lot of attention, but users are complaining that `sort()` takes too long. Not knowing what's wrong with your implementation, you take DSA[a] and learn that you've got shit for brains. You want to rewrite `sort()` but are worried that it might break the interface. However, you remember that interface $\neq$ implementation, so you rewrite `sort()` (using something like merge sort) pushing this new implementation into production, and bragging about how `sort()` now runs in $O(n \log n)$ time.
>
> ---
> [a]DSA: Data Structures and Algorithms

Encapsulation

We want to abstract away complexity (when appropriate) into an interface for ease of use.

Policy and Mechanism

> **Definition: Policy and Mechanism**
>
> A **policy** is a high-level rule or guideline that governs the *behavior* of a system.
>
> -
>
> A **mechanism** is the implementation that is used to *enforce* the policy.

It is important to note that keeping policy and mechanism independent of one another is crucial. By separating policies from the underlying mechanisms, it becomes easier to change or modify policies without affecting the core functionality or technical implementation. This approach provides the ability to update policies independently from the underlying mechanisms, promoting modifiability, maintainability, and customization when designing software.

1.4 Why is the OS Special?

> **Definition: Standard and Privileged Instruction Set**
>
> The **standard instruction set** is the set of hardware instructions that can be executed by anybody.
>
> -
>
> The **privilaged instruction set** is the set of hardware instructions only the kernel can execute. When an application wants to execute a privilaged instruction, it must ask the kernel to execute it for them.

The OS is special for a number of reasons. Mainly, it has *complete* access to the privileged instruction set, *all* of memory and I/O, and mediates applications' access to hardware. This implies that the OS is *trusted* to always act in good faith. Thus, the OS stays up and running as long as the machine is still powered on (theoretically), and if the OS crashes, you're fucked lol.

1.5 Miscellaneous

Below are a list of miscellaneous topics.

1.5.1 Definitions

> **Definition: Instruction Set Architectures**
>
> An **instruction set architecture (ISA)** is the set of instructions supported by a computers. There are multiple (all incompatible) ISA's and they usually come in families.

ISA's usually come with privilaged and standard instruction sets.

> **Definition: Platform**
>
> A **platform** is the combination of hardware and software that provide an environment for running applications.

Common platforms include: Windows, [Mac, i]OS, Linux.

> **Definition: Binary Distribution Model**
>
> The **binary distribution model** is the paradigm of distributing software in compiled or machine code in the form of executables.

The binary distribution model is good for performance and security, but lacks in flexibility and is dependent on the platform you compile it for.

> **Definition: Portability**
>
> **Portability** refers to the ability to be adapted to different platforms with minimal modifications to the source code.

Portability is important if you're an OS designer because you want to maximize the number of people using your product $\implies$ your OS should run on many ISA's and make minimal assumptions about specific hardware.

Chapter 2

Resource Types

This section covers three types of OS resources: serially reusable, partitionable, and sharable.

> **Definition: Graceful Transition**
>
> A **graceful transitions** refers to the process of transferring control between two jobs such that there are no resource conflicts.

A graceful transition maintains system stability, data integrity and therefore cleanly releases resources. They typically ensure that users leave resources in a clean state; i.e. each subsequent user finds the resource in a "like new" condition.

2.1   Serially Reusable

> **Definition: Serially Reusable Resource**
>
> **Serially reusable resources** are resources that can be used by a single process at a time (sequentially) and are not designed to be shared in parallel.

These resources require access control mechanisms to ensure that only one process can access them at any given time. This control ensures a graceful transition between users and prevents conflicts or data corruption that may arise from concurrent access.

> **Example: Printing Process**
>
> Printers are a serially reusable resource: multiple job can use it but only a single job will be printed at a time.

2.2   Partitionable

> **Definition: Partitionable Resource**
>
> **Partitionable resources** can be divided up (or *partitioned*) into smaller, disjoint[a] segments.
>
> ---
> [a]Disjoint: Independent of one another.

These resources require access control mechanisms to ensure that each segment is *contained*[1] and *private*[2]. Partitionable resources can be temporarily allocated (e.g. RAM, CPU *time slice*, etc.) or permanently allocated (e.g. Disk storage[3], database tables, etc.).

---
[1]Contained: Resources outside of a partition are not accessible.
[2]Private: External users cannot access the resources in your partition.
[3]Disk storage is permanently allocated until it isn't. You can use something like `fdisk` (in Linux) to modify partitions.

> **Example: Memory Mania and Disk Division**
>
> Memory can be partitioned, allowing multiple unique processes to access their own allocated memory space independently.
>
> -
>
> Disk storage can be partitioned into separate logical volumes! This is commonly used to dual-boot different operating systems. Recently, M1($/2ish$) Apple products can now run Linux on bare metal (still in beta !) via Asahi Linux!

Graceful transitions are still necessary in partitionable resources! Partitionable resources that aren't permanently allocated need to clean up after themselves.

2.3   Shareable

> **Definition: Shareable Resource**
>
> **Shareable resources** are usable by multiple *concurrent* clients. They need not "wait" for access nor do they "own" a particular subset of a given shared resource.

These resources require access control mechanisms to ensure that the shareable resource is used in a controlled and secured manner.

> **Example: Cloud Crazy**
>
> The cloud (e.g. Google Drive, Oracle Cloud, etc.) is a powerful shared resource! It enables multiple concurrent users to access shared folders and files, facilitating simultaneous editing and collaboration.

Graceful transitions typically are not necessary since a shareable resource generally doesn't change state *or* doesn't require any clean up. In the example above, while the cloud files change state, there is no cleaning up to do, so a graceful transition is not necessary (what's clean doesn't need cleaning).

Chapter 3

Services

The OS provides services in a multitude of ways. This section will introduce and explain how services are provided throughout the software stack.

3.1 Subroutines

> **Definition: Subroutine**
>
> A **subroutine** in the context of operating systems is a small, self-contained and reusable portion of code that performs a specific function.

Subroutines are usually called directly, and operate like normal code (stack manipulation), and are typically seen in higher layers of the OS stack. They are fast, but usually cannot use the privileged instruction set. Furthermore, they are usually not language agnostic. The most common way to implement these subroutines are libraries!

3.2 Libraries

One way the OS provides services to users is via libraries. Standard utility functions such as `malloc` can be found in libraries (in this case, `stdlib.h`). So what exactly is a library?

> **Definition: Library**
>
> A **library** is a collection of code modules that encapsulate common operations, algorithms, and functionality.

> **Abstraction: Libraries**
>
> Most systems are equipped with a wide range of standard libraries, which are designed to be reused. These libraries encapsulate complexity and provide an additional layer of abstraction, simplifying problem-solving.

> **Example: DSA Doozy**
>
> In DSA, you likely had to implement different types of data structures (linear, hierarchical, graphical, etc.) and algorithms (search, divide/conquer, dynamic programming). Imagine your surprise when you find out most of these data structures and algorithms have already been written (and probably perform better than your implementation, no offense).

3.2.1 Bind Time

The choice of library bind time depends on multiple factors that include (but are not limited to): performance requirements, deployment and distribution considerations, and dependency management.

> **Definition: Static**
>
> **Static** libraries are precompiled code modules that link directly to the executable at compile time. They allow for efficient standalone executables, but they result in larger file sizes and require recompilation if the library is updated.

One easy example of a static library is `libc`, or the `C` standard library! It encapsulates a myriad of commonly used operations, algorithms, and functionality when programming in `C` like everyone's favorite `malloc()`.

> **Definition: Shared/Dynamic**
>
> **Shared/Dynamically Linked** libraries are separate files from the load modules that can be loaded and shared by multiple concurrent processes. They are loaded and linked to the executable during runtime.

One thing to note about shared libraries is that they cannot define or include global data storage. Moreover, called routines must be known at compile time since the fetching of the code is the only thing that is delayed until runtime.

3.3 System Calls

> **Definition: System Call**
>
> A **system call** is when users request functionalities from the operating system that are a part of the privileged instruction set.

System calls allow for the use of the privileged instruction set and interprocess communication, so why don't we just make everything a system call? System calls are *slow*[1]. Thus, we typically like to reserve system calls for operations that *require* the privileged instruction set.

> **Example: System Call Stress**
>
> System calls sound like a big deal, but you have already been introduced to them! Some include:
>
> (i) File I/O: Reading from or writing to files on a disk require system calls since they require privileged instructions.
>
> (ii) Memory management: Though functions like `malloc()` itself isn't a system call, it is implemented by calling system calls!
>
> (iii) Process management: Only the kernel can *directly* create/destroy processes and ensure process privacy and containment.
>
> (iv) Interprocess communication: Mainly for security reasons, communication between processes require privileged instructions.

Most of the time, everything related to a given system call is dealt with in the kernel. However, there are instances when the kernel will outsource tasks via direct calls to *untrusted*[2] code, waiting for a response, then returning to the calling process.

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[1]System calls are between 100 and 1,000 times slower than standard subroutine calls!

[2]Untrusted: Not guaranteed to be secure.

3.3.1   Trusted Code

Not all trusted code must be inside the kernel! If code doesn't *need* to access kernel data structures or execute privileged instructions, they might sit outside of the kernel layer.

> **Definition: Trust**
>
> **Trusted** code is guaranteed to be secure and will perform correctly. That is, it is safe for the operating system to run it.

> **Example: Lazy Login**
>
> A login manager/application is a great example of a program that is trusted but doesn't sit inside the kernel. When you login, the kernel will outsource the job to the login application!

3.4   Messages

Another way of service delivery is via messages that are exchanged with a server via system calls.

> **Advantages**
>
> Messages allow users to send and receive requests from anywhere! They are also highly scalable and can be implemeneted in user-mode code.

> **Disadvantages**
>
> Messages are *slow*[a] and are limited to operate on process resources.
>
> ---
> [a]Messages are between 1,000 and 100,000 times slower than subroutine calls!

3.5   Middleware

Middleware refers to software components that are essential for a particular application or service platform but do not sit inside the OS. They bridge the gap between the application and underlying OS, providing additional functionalities and services.

> **Example: Middleware Madness**
>
> Some examples of middleware include database systems, web servers (like Apache and Nginx), distributed computing platforms (like Hadoop and Zookeeper), and cloud computing platforms like OpenStack.

We prefer middleware over implementing such functionalities directly in the kernel because kernel code is expensive and risky since kernel-level issues can impact the stability of the entire system! Instead, middlware is typically developed in user mode, making it easier to build, test, and debug[3]. Moreover, it is more portable, meaning it can be used across different operating systems without modification!

---

[3]If the middleware crashes, it can be restarted independently of the entire system, minimizing its impact on the overall OS stability.

Chapter 4

Interfaces

How do processes communicate with the OS? Interfaces! There are two main types: API and ABI.

> **Abstraction: Interfaces**
>
> Interfacess introduce a layer of abstraction, allowing programmers to focus on *what* they need without worrying about *how* it's implemented!

4.1 Application Programming Interface

> **Definition: Application Programming Interface**
>
> The **application programming interface (API)** provides a standardized set of rules and policies (at the source code level) that govern how different software components can communicate with each other.

API's are the basis for software portability, allowing a program to be compiled for a particular architecture or OS. That is, programmers can recompile for different targets without changing the source code, provided that the API is consistent. To do this, we link our program with OS-specific libraries that implement the funcitonality specified by the API.

Thus, when the program is compiled and linked using an API-compliant system, the binary executable will be compatible[1] with any other API-compliant system! Well-defined API's allow us to create interoperable applications and libraries that are platform/system independent, promoting software portability, reusability, and simplicity when building complex systems!

4.2 Application Binary Interface

> **Definition: Application Binary Interface**
>
> The **application binary interface (ABI)** defines the low-level binary interface that allows compiled programs to interact with the underlying system and hardware.

ABI's govern how DLL's are structured and how they interact with programs at a binary level. But how? ABI's define how data is represented in memory and passed between functions and across different modules! This includes details like register usage, linkage conventions, parameter passing conventions, and stack layout. They also connect the API to the specific hardware, translating source-level instructions to actual machine level instructions.

Once a program is compiled using an ABI-compliant system, it can run unmodified (i.e. without recompilation) on any other system with the same ABI! This ensure that a single binary can service all ABI-compliant systems. Hence, they are usually intended for end-users and software deployment.

---

[1] An API-compliant program will compile and run on any system that supports the same API.

> **Corollary: Libraries**
>
> Libraries are accessed through API's! The API provides source-level definitions for how to access the library, and is readily portable between systems. While DLL's are also accessed via an API, the loading mechanism is specified by the ABI.

4.3 Best Practices for Interoperability

Standalone programs are useless! All useful programs use system calls, library routines, operate on external files, exchange messages, etc. That is, they all utilize OS services! Thus, if the interface changes, these programs will fail. Thus, API requirements are frozen (finalized) at compile time. This means:

 (i) Execution platforms must support the interfaces.

 (ii) All partners/services must support the interface protocols.

 (iii) The API must be backwards compatible

That is, API's need to be *stable* in order to support interoperability! API's need to be rigorously specified and standardized[2]. Thus, the developers that use the API are encouraged to be compliant with the API specifications to ensure that their program will survive updates.

> **Example: New Version New Problems**
>
> Suppose you are writing an application for an OS running on version 0.6.8, and being the genius programmer you are, find an exploit that goes around the OS API to make your app run faster. Everything runs fine until version 0.6.9. Confused, you find that the developers hate you in particular and decided to patch the exploit you used. Having learned your lesson, you have to rewrite that entire feature, being compliant with the API.

Interoperability requires both parties to honor their side of the contract: Standard bodies must keep the interface stable, while developers must be compliant with the API if they want their products to survive new updates.

> **Aside: Side Effects**
>
> > **Definition: Side Effect**
> >
> > A **side effect** is occurs when an action on one object has *non-trivial*[a] consequences.
> >
> > ---
> > [a]Non-trivial: Effects that are not included in the interface specifications.
>
> Side effects are inevitable, but are not the end of the world! They usually happen due to shared state between independent modules and functions. Thus, developers should ignore side effects and continue being compliant with the interface as they *should* be patched. In general, try to avoid exploiting side effects since they are not guaranteed to be there or maintained!

---

[2]Standard body: Most big projects (like Linux) have standard bodies that manage the interface definitions so as to maintain stability!

Chapter 5

Abstraction

Recall that we like abstractions in Computer Science. Life is easy for high level programmers if they work with a simple abstraction. The OS is responsible for creating managing, and exporting such abstractions.

> **Example: Hardware Hiding**
>
> Hardware is fast, but complex and limited, so using it *correctly* can be extremely challenging. Thus, hardware is commonly seen as a building block rather than a solution. We provide abstractions to encapsulate implementation details (like error handling and performance optimization) and eliminate behavior that is irrelevant to the user. Thus, abstractions make it more convenient to work with the hardware!

The OS provides some core abstractions that our computational model relies on: memory, processor, and communication abstractions.

5.1 Memory Abstractions

Memory abstractions provide a consistent way to interact with various data storage resources, simplifying the process for users. However, there are some complicating factors that come with abstracting memory.

5.1.1 Complications

The operating system managing these abstractions doesn't have abstract devices having arbitrary properties. Instead, it handles physical devices that may have inconvenient properties. Therefore, the primary goal of OS abstraction is to create an abstract device with desirable properties derived from the physical device that lacks them.

Memory Lifetime

> **Definition: Persistent and Transient Memory**
>
> **Persistent memory** retains data even when power is turned off (long term memory). Examples of non-volatile storage include hard drives and solid state drives.
>
> -
>
> **Transient memory** loses its data when power is turned off (short term memory). An example of volatile storage is RAM.

Managing data in both types of memory presents different challenges and considerations when designing a complex system.

> **Example: File Finding**
>
> When you run a program, all of the variables local to the program are stored in transient memory, or RAM. However, suppose you write to a file `foo` in your program. `foo` is stored in persistent memory! This means that weeks later, if another program wants to access foo (e.g. `cat foo`), the contents you wrote into `foo` will still be there.

Size

There can be a discrepancy between the size of memory operations that the user wants to work with and the size that the physical memory can handle. Thus, being able to manage data manipulation efficiently, especially when data sizes differ, is very important!

> **Example: Caught in 4k**
>
> Hardware usually processes data at the word level[a]. However, when writing a block of data to flash memory, we typically move data in 4k chunks. Therefore, when reading from or writing to memory, we must ensure that data is moved in the appropriate word size.
> _____
> [a]Word sizes are typically 32 or 64 bits depending on the architecture

Latency

> **Definition: Persistent and Transient Memory**
>
> **Latency** (in the context of memory) refers to the time it takes for a process to read from memory.

Note that the latency reading from RAM and from disk are two very different times which lead to varying performance gains depending on which one you optimize for.

Implementation Variety

The same memory abstraction might be implemented using various physical devices. This leads to varying performance depending on which device imlements the abstraction.

> **Example: Caught in 4k**
>
> Storage devices like hard disks, solid-state drives, and optical drives can all be used to implement file storage, but the performance differences vary between the three. (SSD > HDD > optical).

5.2   Interpreters

> **Definition: Persistent and Transient Memory**
>
> An **interpreter** is the module (abstract or physical) that executes commands and "gets things done".

> **Abstraction: Interpreters**
>
> At the physical level, we have the CPU. Directly working with the CPU is not easy, so the OS provides a higher level intepreter!

An interpreter has several basic components:

(i) Instruction Reference: Tells the interpreter which instruction to execute next.

(ii) Repertoire: The set of features that the interpreter supports.

(iii) Environment Reference: Describes the current state on which the next instruction should be executed.

(iv) Interrupts: Situations in which the instruction reference pointer is overridden.

Example: Processing Processes

The process that we interface with is an example of an interpreter. The OS maintains the *instruction reference* (a program counter for a given process). Its source code specifies its *repertoire*, and its stack, heap, and register contents are its *environment*. The OS manages all three of these components. Another thing to note is that no other interpreters should be able to access the process' resources; i.e. the interpreter should be private.

Aside: Implementation

Implementing the process abstraction in the OS is relatively straightforward when dealing with only one process, but in reality, that is seldom the case. When dealing with multiple processes, we have to consider that:

(i) The OS has limited physical memory to hold environment information.

(ii) There are usually only one set of registers (or one per core).

(iii) The process shares the CPU (or core) with other processes!

To address these issues, we need:

(i) A *scheduler* to share the CPU among multiple processes.

(ii) Better *memory management* hardware and software to create the illusion that each process has full access to RAM (when in reality, they don't).

(iii) Access control mechanisms for other memory abstractions to keep our machine secure.

5.3   Communications

Definition: Communication Link

A **communication link** allows interpreters to talk to each other (on the same or different machines).

Abstraction: Communication Links

A communication link at the physical level consists of memory and cables. However, at more abstract levels, we have networks and interprocess communication mechanisms.

Communication links are distinct from memory abstractions for a couple of reasons:

(i) Factors such as network congestion, distance, and hardware limits contribute to variations in speed, latency, and bandwidth. On the other hand, memory access offers more predictability and consistent performance.

(ii) Communication links are often asynchronous[1], introducing additional complexity compared to synchronous memory access.

---

[1]Asynchronous: Data can be sent and received independently of each other. Timing of communication is not guaranteed to be coordinated.

(iii) The receiver in communication links may be reactive, meaning they only perform an operation because the sender initiated it. In contrast, data is usually immediately available when requested via memory access.

> **Aside: Implementation**
>
> If both ends of the communication link are on the same machine, it's trivial: use memory for transferring data! Copy the message from the sender's memory into the receiver's memory *or* transfer *control*[a] of the memory containing the message from the sender to the receiver. To implement communication links across machines, we have to consider the following:
>
> *(i)* We need to optimize the cost of copying data.
>
> *(ii)* Memory management can become very tricky (especially when manipulating ownership!).
>
> *(iii)* We need to include complex network protocols into the OS itself. This raises new security concerns that the OS might need to address.
>
> *(iv)* We need to be able to deal with message loss, retransmission, etc.
>
> ---
> [a]Transferring control: Change who owns the memory segment!

5.4 Generalizing Abstractions: Introduction to Federation Frameworks

Rather than applications dealing with varied resources, we can make many different things *appear*[2] the same by using a unifying model! Usually, these unifying models involve a federation framework.

> **Example: Computer Communism**
>
> A Portable Document Format, or PDF, is the unifying model for printed output. If we want to print something to a printer, as long as the document is in the PDF format, it will know how to print it!
>
> -
>
> SCSI, SATA, and SAS are standard ways to interface with hard disks and other storage devices (CD, SSD, etc.).

> **Definition: Federation Framework**
>
> A **federation framework** is a structural design that enables similar (but different) entities to be treated uniformly by creating a single *interface*[a] that all entities must adhere to.
>
> ---
> [a]The *implementation* that supports the interface is specified by the particular entities.

Note that a unifying model need not be the model with the "lowest common denominator"[3]. Rather, the model can include "optional features" which are implemented in a standard way. Why? Some devices may have features that others of the same class do not. Thus, these "optional features" allow us to create a highly modular federation framework while maintaining a common unifying model.

---
[2]We want to *abstract* away the implementation details!

[3]Lowest common denominator: The set of features *all* entities have in common.

> **Example: Pretty Printing**
>
> Suppose you are building a federation framework for printers. Some printers can only print single-sided while others can print double-sided. So, a possible federation framework could require that all devices that classify as printers *must* be able to print *at least* single-sided, with the *optional feature* of double-sided printing. Extending this idea, we can add more optional features like color printing, DPI settings, etc.

Unfortunately, there may be instances where a particular device may have features that cannot be exploited through a common model. This is the tradeoff we make for a uniform model. There have been arguments both for and against being able to handle such features in a federation framework.

5.5 Layering Abstractions

It is very common practice to create increasingly complex services by *layering* abstractions.

> **Example: Abstract Abstract Abstract!**
>
> A generic file system is an abstraction layer over a particular file system (1). A particular file system layers on top of an abstract disk (2). This abstract disk layers on a real disk (3). Here, a generic file system is implemented with 3 layers of abstraction! This hierarchical structure simplifies development and enhances system scalability.

Layering allows for modularity, easy development of multiple services on multiple layers, and flexibility in supporting various underlying services. Abstractions hide complex implementation details, promoting structured and independent design.

Unfortunately, layers in a system often introduce performance penalties due to the additional indirection they bring. Moving between layers can be costly as it typically involves changing data structures and representations, and may require extra instructions. Moreover, layers may not be entirely independent of one another; for example, lower layers can impose limitations on what upper layers can achieve.

> **Example: Packages Play Hide n Seek**
>
> An abstract network link may hide causes of packet loss, since the lower layer that this abstraction is built off of may hide certain implementation details that are relevant to these issues.

The OS offers numerous abstractions, catering to diverse needs and use cases. Selecting the most suitable abstractions is crucial for achieving optimal results. It involves understanding the trade-offs between higher-level and lower-level abstractions to ensure efficient utilization of system resources and effective application development.

Part I

Virtualization

Chapter 6

The Process

> **Definition: Process and State**
>
> A **process** is a type of interpreter that executes an instance of a *program*[a].
>
> ---
> [a]A **program** is a set of instructions that defines a particular application.
>
> -
>
> A **state** is a mode or condition of being, representable by a set of bits.

When you begin executing a program, it becomes a process. There may be multiple instances of the same program running simultaneously on the same computer. Typically in these cases, each running instance is a separate process.

> **Abstraction: Processes**
>
> Processes are a type of interpreter, an abstraction we covered in the previous section. We can think of it as a virtual private computer.

A process is an *object*[1], characterized by its state and its operations. All persistent objects have state, distinguishing them from other objects and characterizing the object's current condition. OS's objects' state is mostly managed by the OS itself and not by the user code. Thus, we must ask the OS to access or alter the state of an OS object.

> **Example: Priority Process**
>
> The OS maintains information about the current priority of each process in the system. This subset of *state* determines its position in the scheduling queue.

6.1   Process Address Space

> **Definition: Process Address Space**
>
> The **process address space** is the set of addresses visible to the process. This address space is *private*[a] to the process.
>
> ---
> [a]Private: Inaccessible by outside processes.

The process' address space consists of all memory locations accessible by the process. Invalid addresses are those outside its address space, and as such, the process cannot request access to them. Modern operating systems give the illusion that *every* process' address space can (but often don't) include *all* of memory.

---
[1]Object: NOT the OOP object.

6.1.1 Layout

The process address space typically consists of different segments:

(i) Shared Code: Contains the executable code of the program. We do not do self-modifying code in modern computer systems. Thus, this shared code is static while the process is running, meaning they are read/executable only. So, subsequent instances of a program will be accessing the one stored in RAM since it's a *shared resource*.

(ii) Shared Libraries: Like shared code, shared libraries are a *shared resource* that are stored somewhere in RAM. Thus, multiple processes can access these shared libraries concurrently.

(iii) Private Data: Stores global and static variables used by the program. Since private data is read/write, they are *not* a shared resource, and thus is private to a particular instance of a process.

(iv) Private Stack: Like private data, the private stack is private to a particular instance of a process.

All of these must sit somewhere in RAM, but different type of memory elements have different requirements (e.g. *shared* coded is read/execute, *private* stack is read/write).

Example: Linux Layout

Each operating system puts these process memory segments in different places, but here's how Linux does it! Code segments are statically sized and are put at the beginning (e.g. 0x00000000). The data segment (and heap) is placed after the code segment and grows upward. The stack is placed at the very end (e.g. 0xFFFFFFFF) and grows downward. It is crucial that the data segment and stack are **not** allowed to meet!

6.1.2 Code Segment

Definition: Load Module

The **load module** is the output of a linkage editor, where all external references have been resolved and object modules have been combined into a single executable.

The process starts by creating a load module. To make instructions executable, we need to load the code into RAM, as we can't directly run instructions from the disk. Next, we read the code from the load module and copy it into a specific *code segment*[2] within the process's address space. This allows the CPU to fetch and execute instructions from the memory while the program runs. Since the code is static (read/execute only), we can share it among multiple processes, which helps reduce unnecessary duplication of code.

6.1.3 Data Segment

Data also needs to be initialized within the address space of a process. This requires the creation and mapping of a process data segment into the process' address space. The initial contents of the data segment are copied from the load module. In particular, the BSS[3] segments are initialized to all zeroes. Data segments are read/write (and thus private to the instance of the process). The program can grow or shrink this segment (via the `sbrk` syscall).

6.1.4 Stack Segment

Definition: Stack Frame

A **stack frame** serves as storage for procedure local variables, invocation parameters, and save/restore registers.

---

[2]Code segment: A segment we establish in the process' address space to accommodate the code.
[3]BSS: Block Started by Symbol

Modern programming languages are stack-based. Thus, each procedure call allocates a new stack frame, and once it is completed, the corresponding stack frame is popped off of the stack, freeing any memory that was allocated for it. Modern CPU's have built-in stack support. Thus, the stack must be preserved as part of the process state to ensure proper execution and continuity during a process' lifetime.

The size of the stack in a program depends on its activities, such as the amount of local storage used by each routine. It grows larger as calls nest more deeply (since each procedure call allocates a new stack frame!), and once these calls return, their stack frames can be recycled for future use.

> **Corollary: Who Manages the Stack?**
>
> The operating system is responsible for managing the process' stack segment! It is created alongside the data segment when the program is loaded into memory.
>
> Different operating systems implement stack management differently Some allocate a fixed-size stack at the program's load time, while others dynamically extend the stack as the program needs more space.
>
> Across all operating systems, stack segments are usually only read/write for security reasons. This prevents any unintended execution of code in the stack (e.g. buffer overflows) and ensures that it is used exclusively for storing data and variables.
>
> Stack segments are process private, meaning each process has its own unique stack. This isolation ensures that processes cannot interfere with each other's stacks, which is crucial for maintaining system stability and security.

6.1.5 Libraries

Static libraries are added to the load module, so each module includes a copy of the required library code. This means that if a program is linked with a static library, the compiled code of that library is integrated into the load module. So, if there are multiple processes using the same static library, we have code duplication. Another downside is that programs must be re-linked to get newer versions of static libraries.

Shared libraries are loaded into memory once they are required, and are separate from load modules. Thus, once they are in memory, other processes need not reload the library to access it, reducing memory consumption. Since shared libraries are separate files from load modules, the operating system handles loading the required libraries into memory when the program is executed. In contrast to static libraries, shared libraries are easier to upgrade.

6.2 Process Data Structures

> **Definition: Register**
>
> A **register** is a small, fast, storage location within the CPU used to store data temporarily during the execution of a program. They are *much* faster to access than memory since registers are on the CPU.

General registers are used for temporary data storage and arithmetic tasks, while the program counter keeps track of the memory address of the next instruction to be executed. The processor status register contains important CPU status information, and the stack/frame pointers are essential for managing the function calls and local variables.

Each process has its own set of OS resources (e.g. open files, CWD[4], locks for synchronization). Additionally, the OS maintains specific state information for each process, including the process ID (PID), priority, and execution state.

---

[4]CWD: Current Working Directory

6.2.1 Process Descriptors

> **Definition: Process Descriptor**
>
> A **process descriptor** stores all information relevant to the process for process management, scheduling, and resource allocation.

Process descriptors typically include information such as the state to restore to when a process is dispatched, references to allocated resources, and information to support process operations. They are managed by the OS and are also used for security decisions and allocation issues.

Process Control Block

> **Definition: Process Control Block**
>
> The **Process Control Block (PCB)** is the data structure that Unix systems use and is a type of process descriptor. It is used to represent and maintain information about an individual process. It contains various details and state information needed for process management, scheduling, and resource allocation.

A PCB keeps track of a process' unique PID, state, address space information, program counter, priority, and more.

> **Example: What am I Holding?**
>
> Let's look at what the PCB keeps track of in more detail.
>
> *(i)* The unique PID distinguishes processes from each other.
>
> *(ii)* The process state indicates whether a process is running, ready to run, waiting for I/O, or stopped.
>
> *(iii)* Address Space information is stored in the PCB, keeping track of a process' memory layout (virtual memory address space, code/data/stack, and heap segments).
>
> *(iv)* The PCB stores the CPU context when the process is interrupted or preempted, including the values of CPU registers, program counter, and other relevant CPU state.
>
> *(v)* The PCB keeps track of the Parent PID (PPID), so you always know where you came from.
>
> *(vi)* The File Descriptor Table (FD Table) contains the table that maps file descriptors opened by the process, indicating which files the process has access to.
>
> *(vii)* Signal handlers are used for interprocess communication.

6.3 Other Process State

Not all process state is stored directly in the process descriptor! Other process state is stored in several other places:

(i) Application Execution State: The actual execution state of the application, including variables, function signature, and local data, is stored in the process' stack and CPU registers. As the program executes, data is pushed/popped from the stack, and registers are used to hold intermediate results during computation.

(ii) Supervisor-Mode Stack: Linux processes have a separate supervisor-mode stack, used to retain the state of in-progress system calls and to save the state of a process that gets interrupted by

an interrupt or preemption. This ensures that critical syscall information is preserved across privilege level changes or when the process is preempted by higher-priority tasks.

(iii) Other Memory Areas: Additional process state like the heap, shared memory segments, and memory-mapped files, may be stored in various other memory locations outside of the process descriptor.

Chapter 7

Process Handling

We will cover creating, destroying, and running processes in this section.

7.1 Creating a Process

Process can be created in two main ways: by the operating system and by the request of other processes.

The operating system is responsible for creating processes during system boot or when a user initiates the execution of a specific program. When a user starts an application or runs a command, the OS *initializes*[1] the state of a new process for that program.

Processes can also be created by other running processes! When a process wants to create a new process, we use syscalls like `fork` (in Linux) or `CreateProcess` (in Windows). The parent process is the process that initiates the creation of another process by requesting the OS to create a child process with a specific program and initial state. As a result, the child process inherits some characteristics from its parent, like file descriptors and environment variables.

Other than that, child processes are independent of the parent process and execute concurrently with their parent. They typically start executing from the same point as the parent process but can have distinct memory spaces and execution paths.

> **Example: Pipe Up!**
>
> In our pipe lab, we utilized `fork` and `execlp` to mimic the pipe operator (|)! This consisted of spawning child processes from parent processes to execute different commands. In this instance, we created child processes from another process (the parent) using `fork`, and ran a completely distinct program using `execlp`!

7.1.1 The Process Table

> **Definition: Process Table**
>
> A **process table** is a data structure used by the OS to organize and keep track of all currently active processes in the system. Each entry corresponds to a process and contains a pointer to its PCB.

When a new process is created, the operating system generates a new PCB, which serves as the basic per-process data structure. But how do we keep track of these PCB's? Once a PCB is created, the OS will typically place it into a process table. This table allows the OS to efficiently manage and access information about all running processes (tracking state, scheduling, allocating system resources, etc.).

---

[1]Initialize: The OS will allocate memory, setting up the program's initial execution context, and creating a PCB to manage the process.

7.1.2 Creating the Address Space

In addition to a PCB, we also need an address space to hold all the segments it requires for execution! The OS is responsible for creating and managing the address space for each process. Once the address space is created, what does a new process need in its address space?

The OS needs to allocate memory within the address space for various segments (see **6.1 Process Address Space**) and load the program code and data into these segments. After, the OS sets up the initial values of essential registers for the process:

(i) Program Counter will point tot he first instruction to be executed.

(ii) Processor Status will configure CPU flags.

(iii) Stack Pointer will point to the stop of the initial stack frame.

Once these steps are completed, the new process is ready for execution!

7.1.3 Choices for Process Creation

When we create new processes, there are two approaches commonly used in operating systems: starting from a "blank" process and starting from a template[2].

Blank Process

In this approach, a new process is created with no specific state or resources. It is a blank slate with minimal to no predefined attributes. The OS then provides a mechanism to fill in the essential details required for the process to run successfully (like the code, program counter, etc.). This approach is usually used in Windows-based systems (via the `CreateProcess` syscall).

Template Process

In this approach, a new process is created by duplicating the parent/calling process. This new process inherits most of its attributes and resources from the parent (like the code, PC value, open file descriptors, etc.). The child process will then start execution from the same point in the code as the parent. This approach is usually used in Unix-based systems (via the `fork` syscall).

Example: Forking Forking

When forking a process, we need to figure out which process is which! Luckily, the guys designing this were smart enough to write code that does this for us! When we call `fork()`, the return value will tell us if the current process is the child or parent (or if the fork failed). The process is a child, parent, or failure if the return value of `fork()` $== 0$, > 0, or < 0 respectively.

Corollary: Fork/Exec

The forked child shares the parent's code but not its stack. While the stack is *initialized* with the contents of the parent's stack, it is a completely separate stack! Moreover, forked processes do not share their data segments (mostly...).

---

[2]The "blank" approach gives more control to the user in terms of the process' initial state, whereas the template approach is simpler and faster with minimal overhead.

Copy on Write

> **Definition: Copy-On-Write**
>
> **Copy-On-Write (COW)** allows both the parent and child to share the same physical memory pages for the data segment *until it is modified*. When one of the processes attempts to modify the shared data segment (e.g. writing to a variable), the OS will copy the affected memory pages, create a separate data segment for the modifying process, and allows it to write to the new, copied segment. The other process continues to use the original shared data segment, and no copying is required for unaffected pages.

If the parent has a big data segment, creating a separate copy for the child is expensive! So, we initially have the child process *share* the same data segment as the parent and set it up as a copy-on-write.

Exec

Usually, when we fork we want to run a separate process. `exec` is a Unix syscall that replaces the current code and data segment with new program, "remaking" the process into an entirely different one. When a process calls `exec`, it loads a new program into its address space, overwriting its existing code and data segments with the new program's code and data segments. `exec` will also close all file descriptors associated with the old process (except stdin/out/err) to prevent data corruption and/or resource leaks.

7.2 Destroying a Process

Processes terminate for a multitude of reasons: the machine loses power, the program reaches the end of execution, or the OS or another process kills it. In any case, when a process terminates, the OS needs to clean it up its resources in a way that allows for simple reclamation.

7.2.1 Resource Reclamation

The OS must reclaim any resources held by the terminating process. This includes releasing memory allocated to the process, releasing any locks, and terminating access to hardware devices. This ensures that there are no resources wasted or left in an inconsistent state.

7.2.2 Informing Other Processes

The OS will inform relevant processes that the process has terminated. This includes processes waiting for interprocess communications with the terminated process[3], parent, and child[4] processes.

7.2.3 Update the Process Table

The OS needs to remove the PCB of the terminated process from the process table. Doing this frees up the memory occupied by the process descriptor, making it available for new processes.

Before final cleanup, the OS will collect the exit status of the terminated process.

> **Example: How'd You Exit?**
>
> Assume we create a child process to perform some data retrieval. Once the child process terminates, we get the exit code! Depending on the exit code (success or failure), we can react accordingly! If the retrieval failed, we might run it again or terminate ourself! If the retrieval succeeded, we might continue execution.

---

[3]The OS will clean up any shared resources or communication channels to prevent potential resource leaks or data inconsistencies.

[4]A child process that outlives its parent is known as an **orphaned** process. In such cases, the OS will adopt these orphaned process under the "init" process (PID 1) to ensure proper process management.

7.3 Running a Process

Processes must execute code to do their job, meaning they need to run on a core! However, the set of processes ready to run usually outnumber the number of cores we have. Thus, the processes need to share the core(s). Sooner or later, a process not running on a core needs to be put onto one. How do we do this?

7.3.1 Loading a Process

Before we run a process on a core, the core's hardware needs to be initialized to either an initial state or to the state the process was in the last time it ran on that core. To run a process on a core, we need to:

 (i) Load the core's registers with the appropriate values to start/resume process execution.

 (ii) Initialize the stack and set the stack pointer to the appropriate memory location.

 (iii) Set up any necessary memory control structures (like page tables for virtual memory).

 (iv) Set the program counter to the memory location of the next instruction to be executed.

Now that we have done these steps, we can run a process on a core! But how exactly does it run?

7.3.2 Traps and Exceptions

> **Definition: Trap and Exception**
>
> An **exception** is an abnormal/unexpected event that occurs during the execution of a program, disrupting the normal flow of execution. Some exceptions like EOF^a are routine while others like segmentation faults are unpredictable (also known as *asynchronous exceptions*).
>
> ---
> ^{a}EOF: End of File
>
> -
>
> A **trap** is a mechanism that allows the CPU to transfer control from the current process to the operating system or kernel in response to a specific event/condition. Traps typically handle exceptional situations like system calls initiated by user-level processes or other exceptions (like division by zero, page faults).

Asynchronous exceptions are exceptions that are unpredictable and cannot be explicitly checked for by the program itself. Unlike synchronous exceptions which are predictable and are results of specific operations or instructions within a program, asynchronous exceptions can be triggered by external factors or hardware events.

Since asynchronous exceptions are inherently unpredictable, we cannot use typical control structures to handle them. Instead, many programming languages support a `try/catch` block mechanism which forces the developer to handle these exceptions gracefully. Asynchronous exceptions are usually intercepted by the hardware or operating system via a trap. The OS will then handle the exception appropriately.

In addition to handling asynchronous exceptions, traps are used to handle system calls[5]. System calls will cause an exception that will trap into the operating system through a "trap gate". Once inside the OS, the OS will recognize and perform the requested operation based on the syscall number. The OS may use the condition code to indicate the success or failure of the system call. After completing the instruction(s), the OS returns to the instruction immediately after the syscall, allowing the program to continue executing.

---
[5]System calls are defined at the processor level.

> **Corollary: Trap Handling**
>
> Trap handling is a combination of hardware and software mechanisms to respond to exceptions and traps.
>
> When a trap occurs, the hardware uses the trap cause as an index to access a trap vector table, containing the addresses of trap handlers for different types of exceptions/events. The hardware then loads a new processor status word and switches the CPU to supervisor mode. The current process' program counter and processor status are pushed onto the stack to save the state of the program that caused the trap. Then the program counter is loaded with the address of the first level handler (the starting point of the software trap handling).
>
> The first level handler will then push all other registers onto the stack to preserve the full state of the program at the time of the trap. Then, it reviews the cause of the trap (trap type, error codes, etc.). Based on the cause of the trap, the first level handler will choose the appropriate second level handler to handle the specific exception. The second level handler is a specialized routine that deals with the specified exception.
>
> The second level handler will perform the necessary actions to handle the event. Once done, the second level handler will return control to the first level handler, which, in turn, may run more OS code before eventually returning control to the interrupted program (or terminating it, depending on the situation)

The Kernel Stack

The OS typically uses a separate stack, known as the kernel stack, for running in privileged mode. When a trap occurs, it automatically switches to the kernel stack. This isolates the trap handler's execution, ensuring that it doesn't interfere with the user's stack or leave any sensitive data behind.

7.3.3 Asynchronous Events

> **Definition: Asynchronous Event**
>
> An **asynchronous event** is when a program initiates an operation but does not wait for its completion immediately. Instead, the program continues its execution, and when the operation is finished, the OS will notify the program through an *event completion callback mechanism.*

> **Example: Why Wait?**
>
> Some operations like `read()` are worth waiting for, since we need the data from it to do anything useful! Other times, there might be multiple (independent) outstanding operations that can be done while we wait for the current one we're waiting on.

Event completion callbacks are a common programming paradigm, and are implemented via interrupts, which are similar to traps. They are usually associated with things like I/O devices and timers. When an asynchronous event completes, the associated hardware raises an interrupt to the CPU, signaling that the event has occurred. The CPU then interrupts the currently executing program to handle the event. The OS will then execute the corresponding event completion callback, which allows the program to respond to the event promptly.

Asynchronous event handling is a common programming paradigm to efficiently manage multiple operations and provide responsive behavior to users (like in websites!).

7.3.4   Limited Direct Execution

> **Definition: Limited Direct Execution (LDE)**
>
> **Limited Direct Execution (LDE)** is an execution model used by operating systems, and consist of two parts. General instructions of a process are directly run on the core without OS intervention. Privileged instructions will cause traps to the operating systems, which then handle the instruction(s) in supervisor mode.

The CPU will directly execute most application code, punctuated by occasional traps for syscalls and occasional timer interrupts for time sharing. The main goal is to maximize direct execution and minimize the time spent in the OS.

System calls initiated by user-level processes will cause traps into the OS, which will then execute the instruction(s) in the OS. Timer interrupts are used by the OS to manage time sharing among processes, ensuring a fair time allocation for efficient multitasking.

7.3.5   Signal Handling in User-Mode

> **Definition: Signal**
>
> A **signal** is an event or notification generated by the OS or other processes to inform a process about exceptional conditions, operator actions, or communication events.

The OS defines various types of signals, each with a unique purpose (e.g. SIGSEGV is a segmentation fault signal). When a process receives a signal, we can:

 (i) Ignore the signal, pretending it never happened.

 (ii) Designate a handler function that executes when the specified signal occurs. This lets processes respond to different signals accordingly.

 (iii) Let the OS generate a default action, which is typically to apply the default action associated with the signal that was sent. Typically, the default action is to terminate the process or generate a *core dump*[6].

User-mode signal handling is analogous to hardware traps/interrupts, but instead of being raised by hardware events, signals are implemented and delivered by the operating system to user-mode processes. This enables processes to respond appropriately to exceptional situations.

7.3.6   Managing Process State

Managing process state is a shared responsibility between the process and OS. Each has its role in ensuring proper process resource management.

The process itself will take care of its own *stack and the data stored within it*[7]. The stack is used to manage function calls and local variables during program execution, and thus the process must properly de/allocate memory for its stack and manage the data stored within it.

The OS will keep track of resources that have been *allocated* to the process. This includes managing memory segments allocated to the process, keeping track of any open files and devices the process has access to, and maintaining a kernel stack (see **7.3.2 The Kernel Stack**).

By sharing responsibility, processes can focus on their own execution and data, while the operating ensures fair resource allocation, handles syscalls and traps, and maintains overall system stability and security.

---

[6]Core dump: A snapshot of the process' memory used for debugging.
[7]This implies that they can fuck it up if they aren't careful!

7.4 Blocking and Unblocking Processes

Processes can be blocked when they are waiting for certain conditions to be met, and cannot continue execution until they are met (for various reasons). Blocking a process is a way for the scheduler to temporarily suspend execution until the necessary resources are available or a specific event occurs. This blocking state is crucial for efficient resource management and proper synchronization between processes.

Example: Unblock Me!

There are several reasons a process can be blocked. Here are three:

(i) We are waiting for I/O: Reading from or writing to an external source can take a while, so we should let other processes hop on while we wait!

(ii) Resource Requests: If a resource is currently unavailable, there's no reason for us to sit on the CPU doing nothing! So, we block the process until the requested resource becomes available.

(iii) Synchronization: In multi-threaded applications, processes may need to synchronize their operations to avoid conflicts. We might block a process to wait for a specific event or signal from another process before continuing execution.

Any part of the OS can block or unblock a process! But how do we know when to block or unblock a process? A process can request to block itself through a system call[8]. Un/blocking usually happens in a resource manager, a component in the OS responsible for managing various resources and coordinating their allocation among processes.

Example: Resource Management

When a process request an unavailable resource, the resource manager does the following:

(i) Block the process to prevent the process from being scheduled.

(ii) Yield the CPU to the next process in the scheduler's queue.

When the resource becomes available, the resource manager will:

(i) Unblock the process to allow it to be scheduled.

(ii) Notify the scheduler that the process can now be run.

Effectively managing the un/blocking of processes through the resource manager is essential to ensuring fair resource allocation among processes.

---

[8]You better be sure that someone will unblock you.

Chapter 8

Scheduling

> **Definition: Scheduling/Scheduler**
>
> **Scheduling** is the process of determining which processes should be executed next.
>
> -
>
> A **scheduler** is in charge of scheduling as well as allocating system resources (like CPU time) in a fair and efficient manner.

A scheduler often makes decisions about the order and duration of execution for various tasks competing for resources (e.g. there are almost always more processes than cores). The primary goal of a scheduler is to maximize resource utilization and system efficiency while providing responsive and fair service to all processes.

> **Example: Who Goes Next?**
>
> What job should we run next on an idle core, and for how long should we let it run for? What order should we handle a set of blocked requests for a flash drive? In what order should messages be sent if they are all sent at the same time? Questions like these are all answered (for the most part) with scheduling!

Preface: Optimization Metrics

> **Definition: Metric**
>
> A **metric** is a quantifiable measure or characteristic used to asses the performance of a system.

Different scheduling algorithms optimize for different metrics! Do we want to optimize for throughput? Minimize wait time? Optimize for fairness? How do we decide? Luckily, there's a scheduling algorithm for each of these metrics! No single algorithm will optimize for all of these!

> **Example: Metric Mania**
>
> Different systems have different scheduling goals! Here are a couple examples:
>
> (i) Time sharing is when each user gets an equal share of CPU time. This is good when optimizing for response time (e.g. interactive programs).
>
> (ii) Batch execution optimizes to maximize total throughput. Typically, these types of systems will overlook individual process delays in favor of throughput.
>
> (iii) Real-time systems most likely have a priority system. This way, critical operations that *must*[a] happen on time, while non-critical operations might not even happen!
>
> (iv) Service Level Agreements (SLA) prioritize fulfilling agreements with multiple customers regarding resource allocation and performance. So, we need to find a way to ensure that all SLA's are met.
>
> ---
> [a] The degree of "must" can vary.

The choice of scheduling strategy heavily depends on the system's intended use as well as specific requirements of its users or applications. Generally, we want to optimize for something we can control. Thus, choosing an appropriate scheduling algorithm is important!

Scheduling Metrics

> *Operating Systems, Three Easy Pieces: Scheduling Metrics*
>
> The book introduces two metrics to measure the performance of the scheduling algorithms discussed in this section: turnaround and response time.
>
> > **Definition: Turnaround Time and Response Time**
> >
> > **Turnaround time** is defined to be the time it takes for a job to complete once it arrives on the process queue. Formally, we define $T_{turnaroundtime} := T_{completion} - T_{arrival}$.
> >
> > -
> >
> > **Response time** is defined to be the time it takes for a job to get scheduled for the first time once it arrives on the process queue. Formally, we define
> > $T_{responsetime} := T_{firstrun} - T_{arrival}$.
>
> To begin, we make a list of assumptions about processes, relaxing them as we go.
>
> (i) Each job runs for the same amount of time.
>
> (ii) All jobs arrive at the same time.
>
> (iii) Once started, each job runs to completion.
>
> (iv) All jobs only use the CPU (i.e. no I/O)
>
> (v) The run-time of each job is known.

8.1 The Process Queue

> **Definition: Process Queue**
>
> The **process queue**[a] is the list of processes that are ready to run on the CPU. Processes that are not ready to run are either not in the queue, at the end of the queue, or ignored by the scheduler.
>
> ---
> [a]Typically, the process queue is organized based on the scheduling algorithm we use.

> **Example: Policy and Mechanism**
>
> Scheduling is a great example of policy and mechanism (see **1.3 Policy and Mechanism**). The policy determines which process runs next (by defining priorities and fairness). This policy is usually determined by the system's objectives and which metrics it's trying to optimize for. The mechanism is the implementation of such policies: managing process queues, *dispatching*[a], updating process states, and handling interrupts/context switches.
>
> Notice that the policy and mechanism are independent of each other! The policy layer is not concerned with the low-level details of dispatching, context switches, etc. The mechanism, in turn, follows the guidelines set by the policy to ensure that the system operates as desired.
>
> ---
> [a]Dispatching: Moving processes on/off of the CPU.

8.2 Preemptive and Non-Preemptive

> **Definition: Preemptive and Non-Preemptive Scheduling**
>
> **Preemptive scheduling** is when the OS will *forcibly* interrupt a running process to allocate the CPU to another process. The scheduler has the ability to interrupt a process before it completes its execution, ensuring that all processes get a fair share of CPU time.
>
> -
>
> **Non-preemptive scheduling** is when a running process retains control of the CPU until it *voluntarily* relinquishes control or completes its execution. The scheduler does not forcibly interrupt a process, allowing it to run to completion or until it *explicitly* yields the CPU.

Preemptive

Advantages	Disadvantages
(i) Faster response times: We don't have to wait for a long running process to finish!	(i) They are more complex to build: Preemptive scheduling requires additional mechanisms to handle context switches and process state saving, making it harder to implement.
(ii) Fair usage: Each process will run for a fair amount of time.	(ii) Possibly lower throughput: Frequent preemptions can incur some overhead and reduce overall system throughput.
(iii) Good for real-time and priority scheduling: Preemptive scheduling can handle time-critical tasks and support different priority levels effectively.	(iii) Potentially higher overhead: Context switching and frequent preemptions can lead to higher overhead in the system.

Non-Preemptive

<table>
<tr><td>**Advantages**</td><td>**Disadvantages**</td></tr>
<tr><td>

(i) They are simple: I mean, it's pretty straightforward.

(ii) Low overhead: Since the scheduler doesn't interrupt running processes, there is less overhead involved in context switching.

(iii) High throughput: Processes generally run to completion, which usually leads to better overall system throughput.

</td><td>

(i) Slower response times: Processes may have to wait for a long time before getting CPU time if a long running process is scheduled before it.

(ii) Unfair usage: Longer running process will inherently take more CPU time than shorter ones.

(iii) Bad for real-time and priority scheduling: Time-critical tasks may not run on time if a process is running and the deadline passes.

</td></tr>
</table>

Examples: Expectations v. Reality

Example: Throughput Trouble
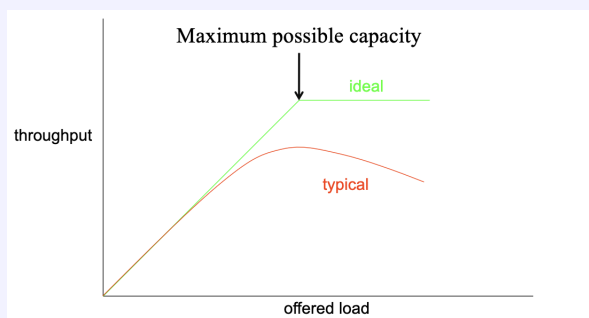
This happens because scheduling isn't free! It takes time to dispatch a process (overhead). More dispatches mean more overhead (lost time). Consequently, less time (per second) is available to run processes. Naturally, we can try minimizing the performance gap by reducing the overhead per dispatch and minimize the number of dispatches.
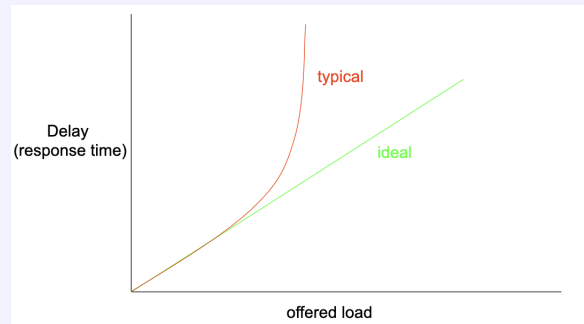
This happens because real systems (unfortunately) have finite limits (like queue size). When limits are exceeded, requests are typically *dropped*[a]. From the requester's view, this looks like an infinite response time since the request isn't begin serviced at all! Even if there are mechanisms like automatic retries (e.g. TCP retransmissions), the retries themselves could also be dropped, further exacerbating the situation. During these periods of heavy loads, the system performance drops severely since overheads like context switching and memory management will explode. Careful system design and resource management can help to minimize this problem, but it is not guaranteed to *fix* the problem.

[a]Dropped: We simply don't process the request

Graceful Degradation

Definition: Overload and Graceful Degradation

A system is said to be **overloaded** when it can no longer meet its service goals.

- -

Graceful degradation ensures that the system will continue service, but with degraded performance.

When a system is overloaded, we want to use the graceful degradation principle to at least do *some* work. We *never* want to allow throughput to drop to zero. This will allow response times to grow without limit; i.e. this will lead to infinite response times!

8.3   Non-Preemptive Algorithms

8.3.1   First Come First Serve

The First Come First Serve (FCFS) algorithm consists of running the processes in the order that they arrived. We run the first process on the ready queue until it completes or yields. One of the primary characteristics of this algorithm is that it has highly variable delays since it relies on the process order.

Operating Systems, Three Easy Pieces: FIFO/FCFS

What happens when we relax assumption *(i)* (See **Scheduling Metrics**)? Well, long-running processes will monopolize CPU time, delaying the execution of shorter processes! This results in poorer performance if a long-running process runs first.

While FCFS ensures that all processes will eventually be served, it may not be the most efficient since it can result in poor utilization of the CPU and inefficient response times. Long-running processes will monopolize CPU time, delaying the execution of shorter processes.

8.3.2 Shortest Job First

The Shortest Job First (SJF) algorithm runs the processes in the order of their run-times. We run the process with the shortest run-time on the ready queue until it completes or yields. One of the primary characteristics of this algorithm is that it optimizes for throughput (good for batch processing!).

> **Operating Systems, Three Easy Pieces: FIFO/FCFS**
>
> What happens when we relax assumption *(ii)* (See **Scheduling Metrics**)? Well, we run into the same problem as FCFS if the long-running process arrives first! The long-running process will monopolize CPU time, delaying the execution of the other processes!

8.4 Real-Time Schedulers

Real-time schedulers are used in systems with time-sensitive tasks. Deadlines can either be *hard*[1] or *soft*[2].

8.4.1 Hard

Hard real-time schedulers rigorously enforce deadlines through careful analysis and pre-defined schedules. Often times, this means that we know *in advance* the schedule of processes to be run. Therefore, there is no nondeterminism in your scheduler, and it is inherently non-preemptive. These real-time schedulers are uncommon.

> **Example: Deadly Deadline**
>
> Assume you have to write a scheduling algorithm to control a nuclear power plant. If you miss a particular process deadline, your plant will probably blow up. So, you carefully analyze your processes to come up with the *perfect* schedule that will *never* miss a deadline. Since you know the processes in advance, there is no nondeterminism in your schedule.

8.4.2 Soft

Soft real-time schedulers *want* to meet deadlines, but it won't be the end of the world if they don't. So, we want to optimize our scheduler to avoid missing deadlines. We can do so by giving each process a priority level: the higher the priority, the sooner the deadline.

One possible algorithm is Earliest Deadline First (EDF), which will sort jobs based on deadlines, minimizing total lateness.

If deadlines are missed, the system's response depends on its design and may involve dropping the job, falling behind, or dropping future jobs to compensate.

> **Example: Choppy Video**
>
> When watching a video, the reason why it may be choppy at times is because the scheduler will drop certain packets that missed their deadline! Thus, to the end user it appears choppy, probably because their internet sucks (they might be using eduroam).

8.5 Preemptive Algorithms

> **Operating Systems, Three Easy Pieces: Preemptive Algorithms**
>
> When we relax *(iii)* (See **Scheduling Metrics**), we get preemptive algorithms.

---

[1]Hard: Under no circumstances can the deadline be missed.
[2]Soft: It isn't the end of the world if the deadline is missed.

Preface: Implementing Preemption

Preemption can be caused by syscalls or clock interrupts. Before returning control to the process, the scheduler is consulted to determine if there are higher-priority ready processes or any processes that need to be woken up. The scheduler will find the highest priority ready process, switching to it (if it's not the current process), effectively preempting the current process.

We can use clock interrupts to do this. Modern CPU's have a clock peripheral device that can generate interrupts at fixed time intervals. These clock interrupts will temporarily halt the currently running process, transferring control to the scheduler, allowing for preemptive scheduling.

8.5.1 Round Robin

The Round Robin (RR) algorithm consists of assigning a time slice to all processes (usually the same size). Processes are scheduled as they arrive and run until they either block or their time slice expires. After running, the process is put at the end of the process queue. Eventually each process will get a turn to run for its allotted time slice.

Some key characteristics of RR is that this usually results in faster response times (for interactive applications), but since more context switches occur, they can be expensive. Additionally, runaway processes have less impact since they only take a fraction of the overall cycles, and will not run forever.

> **Operating Systems, Three Easy Pieces: Round Robin**
>
> Note that "fair" algorithms like RR will perform poorly in turnaround time. Thus, we use response time to measure such algorithms. Now, relaxing assumption *(iv)* (See **Scheduling Metrics**), we can see that there may be gaps where the CPU isn't doing anything! To remedy this, we want to move the process to the back of the process queue whenever the process halts, *regardless* of how (I/O, interrupt, etc.). This way, the CPU is *always* doing something useful.

8.5.2 Choosing a Time Slice

The duration of the time slice is crucial for optimizing performance. Longer time slices reduce the frequency of context switches, but are bad for response times. Shorter time slices are better for response time, but are more expensive since they require more context switches. Striking the right balance is important!

8.5.3 Cost of Context Switches

When a context switch occurs, the OS goes through several steps, handling the interrupt, saving register values, and invoking the scheduler, all of which incur overhead. Additionally, context switching involves changing the stack and handling non-resident process descriptions. Furthermore, the switch requires mapping out the old and new processes, affecting the efficiency of address space changes. More notably, the loss of instruction and data caches significantly impacts the speed of subsequent instructions, reducing overall performance.

8.6 Priority Algorithms

> **Definition: Starvation**
>
> **Starvation** refers to when processes that have low priority don't run very often or don't run at all.

Priority scheduling assigns each process a particular priority level (higher usually meaning more important). Priority scheduling depends on if the scheduler is preemptive or non-preemptive. Non-preemptive priority schedules simply dictate the order the processes will run in. However, if the scheduler is preemptive, we may have a case where, when a new process is created, it preempts the running process (assuming the new process has higher priority). One concern for preemptive priority algorithms is the possibility of starvation.

8.6.1 Hard and Soft

8.6.2 Multi-Level Feedback Queue

The Multi-Level Feedback Queue (MLFQ) is a technique that uses multiple ready queues with varying time slices to accommodate different types of processes. We want to optimize both response time for interactive tasks and minimize overhead for longer background tasks. The foreground queue with shorter time slices (high priority) is used for quick responses. The background queue with longer time slices (low priority) minimizes overhead.

When a new process enters the scheduler, it is initially placed in the high priority queue. Once its time slice expires, the process is then moved to the low priority queue. Periodically, all processes are moved back to the high priority queue to prevent starvation!

MLFQ achieves acceptable response times for interactive jobs without wasting CPU resources. Additionally, the scheduler dynamically adjusts based on the actual behavior of jobs, providing an automatic and adaptive scheduler!

Chapter 9

Memory Management

There are three primary goals for memory management:

(i) Transparency: Processes should only be able to see their own address space. That is, their address space is isolated, and processes are oblivious of any memory sharing with other processes. This ensures data privacy and security.

(ii) Efficiency: The system should utilize memory efficiently to optimize resource allocation and minimize waste. The allocation and (when necessary) relocation of memory should be performed with low run-time overhead to maximize system performance.

(iii) Protection and isolation: We want to ensure that the data within a process remains protected and is isolated from outside processes. That is, other processes can neither access it nor modify it.

The memory management problem involves several key aspects:

(i) Unpredictability: Processes usually cannot accurately predict the exact amount of memory they will require during execution.

(ii) Continuity Expectations: Processes expect to find their existing data where they left it, implying that processes assume they have a contiguous address space.

(iii) Limited Physical Memory: The total memory required by all the processes may exceed the available physical memory.

(iv) Efficient Process Switching: We need to optimize the delay for copying data.

(v) Low Overhead: The cost of memory management should be minimized to maximize system performance.

Preface: Physical and Virtual Addresses

> **Definition: Physical and Virtual Memory Addresses**
>
> **Physical memory addresses** refer to the actual hardware location of a particular memory block.
>
> -
>
> **Virtual memory addresses** are an *abstraction* over physical memory addresses, and are *not* the same as physical addresses. They represent a contiguous block of memory, when in reality the physical addresses may be scattered.

Virtual memory addresses are used in processes and allow for more flexibility in memory management, but require a virtual to physical translation unit.

Preface: Fragmentation

Definition: Internal and External Fragmentation

Internal fragmentation occurs when there is wasted space *inside* a block of allocated memory. That is, the requester was given more memory than he needed.

- -

External fragmentation occurs when there is free space in the memory that cannot be used to satisfy any memory allocation request since the available free memory is fragmented into smaller, non-contiguous blocks. As a result, the total amount of free memory may satisfy the request, but since the memory isn't contiguous, we cannot fulfill it.

9.1 Fixed Partition Allocation

Fixed Partition Allocation divides the available memory into fixed-size partitions (go figure), and each partition is assigned to a specific process. The number of partitions is pre-allocated and is based off the expected number of processes and their sizes. Each process can only access the partition assigned to it and cannot access the memory allocated to other processes.

This approach is relatively easy to implement and was used in early batch processing systems. The de/allocation of partitions are straightforward and efficient. However, it is not very flexible since it requires a predetermined number of partitions and may lead to inefficient memory utilization if the partition sizes are not well-matched with the actual memory requirements of the processes.

To enforce memory protection, hardware support is often used. Special registers that hold the partition boundaries ensure that each process can only access memory within its allocated partition. However, fixed partition allocation does not use virtual addresses, meaning the processes use the physical addresses directly.

9.1.1 Problems

There are several problems with Fixed Partition Allocation:

(i) Static Allocation: Fixed Partition Allocation requires knowing the exact memory requirements of all processes in advance, making it challenging to handle dynamic memory demands.

(ii) Limitations: The number of partitions defines the maximum number of processes that can be accommodated concurrently. If the partitions are not efficiently sized or the number of processes exceed the partition count, some processes may not be able to run concurrently.

(iii) Inefficient: Some partitions may be unused or underutilized, leading to poor memory utilization.

(iv) Limited Sharing: Processes cannot easily share memory, making it difficult to implement communication and data sharing between processes.

(v) Internal Fragmentation: If partitions are not efficiently sized, they may succumb to internal fragmentation, leading to wasted memory.

Because of these reasons, this approach isn't commonly used in modern operating systems.

9.2 Dynamic Partition Allocation

Dynamic Partition Allocation allows variable-sized partitions which accommodate almost any size requested. Each partition has contiguous addresses, and processes are allowed to access the partitions it requested. These partitions can be shared between multiple processes, and a single process may have multiple partitions with different sizes and characteristics. However, in the basic scheme, memory addresses are still physical, which can lead to external fragmentation and limited address space.

9.2.1   Problems

There are several problems with Dynamic Partition Allocation:

 (i) Not Relocatable: Once a partition is allocated, it is very hard to relocate its contents to another memory location, which can lead to inefficient memory utilization.

 (ii) Not Expandable: Dynamic partitions are limited in their ability to grow/shrink to accommodate changing memory requirements of processes.

 (iii) Limited Support: Dynamic partitions may struggle to support address spaces larger than physical memory, hindering their ability to handle memory-intensive jobs.

 (iv) External Fragmentation: As processes de/allocate memory over time, dynamic partitions can suffer from external fragmentation, leading to wasted memory.

Relocation and expansion can be challenging in dynamic partition allocation because partitions are tied to specific address ranges during execution. Relocating the contents of a partition require updating all the pointers within the contents, which is not always feasible, especially if you don't know which memory locations contain pointers. Additionally, expanding a partition may be challenging since there may not be enough contiguous free space. These limit the usefulness of dynamic partition allocation.

9.2.2   Managing Variable-Sized Partitions

> **Definition: Free List**
>
> The **free list** is a data structure (often implmented with a list or array) that keeps track of all available chunks of unallocated memory.

To manage variable-sized partitions, the memory manager starts with a single large block of memory known as the "heap", and maintains a data structure called the "free list". When a process requests memory, the memory manager will consult the free list, carving a chunk (of the requested size) and putting the remainder back onto the free list. When processes deallocate memory, it is put back onto the free list.

9.3   Free-Space Management

Fixed sized blocks are easy to track: we can use a bitmap to indicate which blocks are free.

Variable chunks require more information. Each chunk of memory has a descriptor containing information about its free status, chunk size, and a pointer to the next chunk. These chunks are typically organized into a linked list.

Variable sized partitions are not as subject to internal fragmentation since processes, in theory, request the exact amount of memory needed. However, they are subject to external fragmentation. We can minimize external fragmentation by consulting an algorithm to determine how we manage our free list.

9.3.1   Best Fit

The best fit algorithm will search for the *smallest* available chunk that meets the size requirements. This minimizes memory waste and reduces internal fragmentation.

Advantages	Disadvantages
(i) Increased odds of a (near) perfect fit.	*(i)* An exhaustive search is necessary. *(ii)* Quickly creates small fragments.

9.3.2   Worst Fit

The worst fit algorithm will search for the *largest* available chunk that meets the size requirements. This tries to minimize memory waste by creating large fragments.

Advantages	Disadvantages
(i) Tends to create large fragments.	*(i)* An exhaustive search is necessary. *(ii)* Over time, small fragments are inevitable.

9.3.3   First Fit

The first fit algorithm will search for the *first* available chunk that meets the size requirements. This reduces overhead since there's no need (potentially) to search exhaustively.

Advantages	Disadvantages
(i) Creates random sized fragments. *(ii)* Doesn't require an exhaustive search.	*(i)* The first chunks quickly fragment *(ii)* Over time, the searches become longer.

9.3.4   Next Fit

The next fit algorithm will search for the *first* available chunk that meets the size requirements *starting from the last allocation point* instead of the beginning of the free list. This reduces overhead and tries to minimize fragmentation.

Advantages	Disadvantages
(i) Creates random sized fragments. *(ii)* Reduces overhead since we don't start from the beginning.	*(i)* Over time, memory chunks still fragment. *(ii)* Over time, the searches become longer.

9.4   Coalescing Partitions

Coalescing partitions is a technique used to reduce external fragmentation in variable-sized partition allocation algorithms. When a process frees a chunk of memory, the memory management system checks if the neighboring chunks are also free. If they are, the system combines them into a larger, contiguous block, reducing fragmentation.

> **Operating Systems, Three Easy Pieces: Free-Space Management**
>
> To simplify the coalescing process, we can organize the free list such that neighboring chunks are placed close to each other. One way to do this is by ordering the free list by addresses, making it more efficient to find neighboring chunks and merge them when necessary.

Coalescing helps minimize external fragmentation by reducing the number of small, unusable gaps between allocated memory blocks. However, it is worth noting that it doesn't *completely* eliminate external fragmentation since it can only merge *contiguous* chunks.

When multiple processes operate in parallel, it's challenging to predict which process will dominate and how they will interact, leading to potential fragmentation issues. The fraction of space typically allocated depends on the number and size of processes running; if a significant portion of memory is allocated, coalescing becomes less effective due to limited free space.

Additionally, the speed of allocated memory turnover affects coalescing; processes holding memory chunks for extended periods reduce the effectiveness of coalescing. Note that coalescing only minimizes fragmentation since external fragmentation will *always* occur over time.

9.5   Buffer Pools

Certain chunk sizes are requested more frequently than others. Key services like I/O, network protocols, etc. usually work with fixed-size buffers. Thus, we can reserve special pools of fixed-size buffers for popular buffer sizes.

> **Definition: Buffer Pool**
>
> A **buffer pool** is a reserved section of fixed-sized memory buffers used to handle frequently requested memory sizes (like Reiher's favorite 4K), reducing memory management overhead and external fragmentation.

Buffer pools are used to handle frequently requested memory sizes efficiently. When there are popular buffer sizes, the operating system can reserve special pools of fixed-size buffers. When a request for a matching buffer size arrives, it is taken out of the buffer pool as opposed to the free list. This reduces external fragmentation and memory management overhead.

However, the OS needs to determine an appropriate size for the buffer pool. Too small and it might not improve efficiency. Too large and it might lead to a lot of unused buffer space. It is also worth noting that buffer pools will only satisfy *perfectly* matching requests, since otherwise we get internal fragmentation.

9.5.1   Sizing

We dynamically adjust the size of the buffer pool based on the system load and buffer availability. When the pool runs low on fixed-size buffers, we simply acquire more memory from the free list[1] and divide it into new buffers. When the pool is too large, we release some buffers back into the free list. We can tune these thresholds (low space and high space) to determine when to adjust the buffer pool size. This approach makes the system highly adaptive to changing workloads and memory requirements.

9.6   Memory Leaks

> **Definition: Memory Leak**
>
> A **memory leak** is when memory is allocated but never freed, causing the memory to remain occupied indefinitely.

Memory leaks in the context of buffer pools occur when a process is done with a buffer, but fails to free it. This causes the buffer to remain in the pool indefinitely, wasting memory. Long running processes with memory leaks can result in substantial memory waste over time. Addressing memory leaks is crucial if we want efficient memory utilization.

---

[1]If the free list gets dangerously low, we ask each major service with a buffer pool to return space.

9.7 Garbage Collection

Garbage collection (GC) is a technique to address memory leaks and reclaim unused memory. Instead of relying on processes to release memory on their own, garbage collection monitors the amount of free memory left on the system. When there is *memory pressure*[2], garbage collection is triggered.

The system will search the data space to identify all reachable objects, noting their address and size. Then, any unreachable objects (inaccessible memory) is then reclaimed and added back into the free list. This ensures that memory is efficiently utilized and helps prevent memory leaks!

9.7.1 Determining Accessible Memory

In general, we want to identify and reclaim memory that is no longer used. To do this, we do the following:

(i) Find all pointers in allocated memory: We need to traverse *all* allocated memory to locate the pointers that reference other objects/data.

(ii) Determine the size of each pointer: We must determine the size and extent of the memory region each pointer references.

(iii) Determine what is/n't pointed to: We need to identify objects that are still accessible and in use by actively referenced pointers.

(iv) Free inaccessible memory: We put all inaccessible memory back into the free list.

GC can be difficult because it requires comprehensive scanning of the entire memory space to identify references and determine object boundaries. Furthermore, it also needs to be able to handle complex references (e.g. cyclic data structures) for accurate identification of unused memory. Additionally, GC takes time, and therefore can slow down system performance.

9.7.2 Problems

There are several problems we need to address:

(i) Identifying pointers are *hard*. Locations in a program's data or stack segments may *appear* to contain addresses but are actually just data (that *resembles* addresses). We need to accurately identify valid pointers to avoid reclaiming active memory.

(ii) Even if pointers are identified, we need to determine if they are still accessible and in use! This requires recursive analysis of dynamically allocated data structures to ensure that all referenced memory remains reachable. Even so, statically allocated data structures are harder to analyze.

(iii) We also need to determine the size of each object pointed to, which can be challenging! Measuring exact boundaries may be hard for complex data structures or objects with variables sizes.

---

[2]Memory pressure: When the amount of free memory becomes dangerously low.

9.8 Memory Compaction and Relocation

GC is simply another method to release memory, and therefore doesn't significantly impact fragmentation. Ongoing memory de/allocations can prevent coalescing, leading to fragmentation over time[3].

To counter this, we can compact active memory to one end, coalescing the other end to eliminate fragmentation! However, this requires relocation, which is extremely complicated, since we need to update all memory references correctly.

When a process is relocated, all addresses within the program will become invalid, resulting in potential errors and crashes. We would need to:

(i) Update all references in the code segment (e.g. calls and branches to other parts of code) to point to the correct memory addresses in the new location.

(ii) Update referees to variables in the data segment to point to the correct addresses in the new location.

(iii) Ensure that new pointers are adjusted to point to the correct addresses after relocation.

To solve the relocation problem, we can make the process location independent! By doing this, we can avoid the complexities of update memory references, *abstracting* away *(i) – (iii)*! We want to enable processes to execute in *any* part of memory without adjusting memory addresses.

We can achieve this using various techniques:

(i) Relative addressing: We can use offsets instead of absolute memory addresses to allow processes to be loaded into different memory locations with no address modifications.

(ii) Base and Bounds Registers: We can use hardware registers (base and bound registers) to automatically adjust memory references at runtime. These registers keep track of the base address and size (bound) of the process' memory space, allowing the CPU to translate relative addresses into absolute addresses during execution.

(iii) Virtual Memory and Paging: We can use VM techniques like paging to abstract the physical memory from the process' address space. This way, the process can work with the virtual addresses that get translated to physical addresses, making the process independent of its location.

> **Abstraction: Virtual Memory**
>
> Virtual memory is an *abstraction* over physical memory! A virtual address is *not* the same as its corresponding physical address, and requires a translation unit to convert between the two. However, this is a small price to pay for making memory relocation *significantly* easier!

9.8.1 Segment Relocation

Memory segment relocation is a technique that involves organizing a process' address space into multiple segments, each representing a contiguous block of memory with a specific purpose (see **6.1 Process Address Space**). The segments are then moved as a unit during relocation.

9.8.2 Base and Bounds Registers

Computer architecture may include special relocation registers known as segment *base registers*. These registers hold the starting address of each segment in physical memory. When the CPU accesses a memory location, it will add the address to the address of the base register, translating the virtual address to the physical address!

When a program is loaded into memory, the OS sets the base registers to the start of the program. When relocating, we simply update the base register accordingly. This way, the program can continue to run smoothly regardless of where it is located in physical memory.

---

[3]Frequent allocations can starve coalescing, reducing its effectiveness.

We still need to protect our memory! Protection refers to preventing a process from accessing memory outside its allocated memory. To achieve this, we utilize a length (or limit) register, often called the *bounds register*, which specifies the maximum valid offset from the start of the segment. Any address greater than the limit is considered illegal and should be inaccessible to the process.

When processes attempt to access an illegal address, the CPU triggers a segmentation exception or trap. This exception traps into the OS allowing it to take appropriate action (e.g. terminating the process or controlling the violation).

9.9   Swapping

Swapping is a technique to overcome the limitation of physical RAM by temporarily storing inactive processes' memory on disk. When a process isn't actively running (e.g. yields, blocked), its entire memory contents are copied to disk to free up RAM for other processes.

When a process is scheduled to run again, its memory is then copied back from disk onto RAM to continue execution. If the system has relocation hardware, the memory can be placed in different RAM locations, enabling processes to access their memory regardless of their physical addresses. This allows the system to use disk space as a virtual extension of physical memory, giving the *illusion* that each process gets all of RAM to itself.

However, swapping incurs overhead since copying is expensive! The cost of a context switch are *very* high, since we need to:

 (i) Copy all of RAM out to disk.

 (ii) Copy other stuff from disk to RAM.

before the new process can do anything. Moreover, we still cannot exceed the amount of physical RAM, which can limit memory-intensive processes or overall system performance.

9.10   Paging

Paging is a technique that divides both physical memory and virtual address space into fixed-size units[4] called *pages*. The pages in physical memory are referred to as *page frames*, while pages in virtual memory are just called *pages*.

Each virtual page is mapped to a physical page frame, but it's not fixed nor is it one-to-one. Instead, a per-page translation mechanism called a *memory management unit (MMU)*[5], is used to dynamically translate virtual page numbers to corresponding physical page frame numbers.

9.10.1   Big Page Tables

Definition: Translation Lookaside Buffer

The **Translation Lookaside Buffer (TLB)** is the MMU cache that stores a subset of recently accessed page table entries. This improves lookup times since we don't have to access page table entries from main memory for *every* memory access.

Traditionally, page tables were implementing using fast registers in the MMU. But with larger memory sizes and smaller page sizes, there will be a *lot* of pages.

---

[4]Usually 1-4K bytes or words.
[5]The Memory Management Unit (MMU) is hardware (often integrated into the CPU) responsible for handling memory access and virtual-to-physical address translation.

> **Definition: TLB Hit and Miss**
>
> A **TLB hit** is when the required translation is found in the TLB.
>
> -
>
> A **TLB miss** is when the required translation is *not* in the TLB, and an access to the page table is necessary.

To remedy this, TLB's act as a high-speed cache for virtual-to-physical address translations, reducing overhead. When the CPU needs to translate a virtual address, it first checks the TLB. If the translation is found in the TLB, we return it. Otherwise, we need to consult the page table in main memory to retrieve the required page table entry. The TLB is then updated accordingly.

Unfortunately, the TLB has a limited size, and therefore not all entries can fit into it. This lead to the issue of cache invalidation and replacing entries when the TLB is full. Maintaining a high TLB hit ratio is crucial for efficient VM performance.

9.10.2 Swap Space

> **Definition: Page Fault**
>
> A **page fault** is when the required address is not in the TLB, is valid, but is not present (i.e. it is in the swap space or page file).

Since we have more pages than RAM, we need to store some of them somewhere other than RAM. Typically, some pages are kept on disk and are referred to as the *swap space* or *page file*. When a page fault occurs, the OS retrieves[6] the required page from the swap space, loading it into an available page frame in RAM. The program counter is backed up to retry the failed instruction after the page is loaded, allowing the process to continue running.

9.10.3 Ongoing Operations

The MMU has many ongoing operations. Here are three important ones:

(i) Adding/Removing Pages: When the current process dynamically de/allocates memory, the MMU needs to reflect this in the page table. The OS will directly update the active page table in memory to adjust the relevant page mappings. A privileged instruction is used to flush any stale cached entries in the MMU to ensure an accurate mapping.

(ii) Context Switching: When the system switches processes, the MMU needs to switch the appropriate page table for the new process. Each process has a separate page table, and a privileged instruction is used to load the pointer to the new page table. Before the new process begins execution, a reload instruction flushes any previously cached entries, preventing invalid access.

(iii) Page Sharing: Page sharing allows for memory sharing between multiple processes. The page tables can be configured to point to the same *physical* page. This means multiple processes can have access to the same page in RAM. Page sharing can be read/write or read-only depending on access requirements and memory protection mechanisms enforced by the OS. This approach is good for sharing read-only data (e.g. code segments, shared libraries), reducing redundancy.

---

[6]In the meantime, other processes can execute

9.10.4 Demand Paging

Demand paging is a technique where not all pages of a process are loaded into RAM at once. Rather, only pages that are actively being referenced are brought into memory when needed, allowing for better memory efficiency and less overhead during process scheduling and context switching.

Demand paging frees up RAM by keeping the majority of a process' data on disk until it's actually needed, enabling the system to accommodate more processes and improves overall memory utilization. Demand paging utilizes page faults to signal when pages need to be fetched from disk.

One problem of demand paging is performance optimization. Frequent page faults incur overhead since the time it takes to fetch from disk can add up. Efficient page replacement algorithms like *Least Recently Used (LRU)*[7] are used to minimize the number of page faults triggered to ensure that relevant pages are kept in RAM.

9.10.5 Locality of Reference

Locality of reference suggests that the next address a program will access is most likely to be close to the one it just accessed. This is usually present in programs since they often execute sequences of consecutive (or nearby) instructions, have short branches, access data in the current/previous stack frame, and (tend to) access recently allocated heap structures. While there are no guarantees, identifying these trends help reduce the number of page faults.

---

[7]The page that hasn't been accessed for the longest period of time is booted from RAM.

Chapter 10

Virtual Memory

Virtual memory (VM) is a generalization of demand paging, and is a technique that provides a large and uniform address space to each process. It gives the *illusion* that each process has access to a vast amount of memory (much larger than the physical RAM available).

> **Abstraction: Virtual Memory and Paging**
>
> Virtual memory is an *abstraction* over demand paging. It extends the concept of paging by providing a much larger address space to each process by using dynamic paging and swapping.

Processes can directly request segments in this space, and the virtual memory system handles the mapping of virtual to physical addresses via page tables. VM allows processes to run even if their entire address space doesn't fit into physical memory. Instead, only actively referenced portions are loaded into RAM, while the rest sits on disk.

10.1 Replacement Algorithms

Replacement algorithms are the key technology to making virtual memory work. We want to have the relevant pages loaded into RAM when a process needs to access them.

We do this by relying on the principle of locality of reference. Doing this allows us to make smart choices about which pages to keep in memory and which ones to kick to disk.

Page replacement happens when we need to free up space in memory for new pages. Whenever a page fault occurs, we select an appropriate page to replace via an algorithm (like LRU).

10.1.1 The Optimal Algorithm (Belady's Algorithm)

The optimal replacement algorithm replaces the page that will be accessed furthest into the future, minimizing the number of page faults. However, this requires an oracle, and as such, it is impossible to implement. This algorithm is also known as "Belady's Algorithm".

10.1.2 FIFO and Random

According to Reiher (and common sense), these are dogshit so I'm not going to cover them.

10.1.3 Least Frequently Used

The Least Frequently Used (LFU) policy kicks the least frequently used page back to disk. It isn't the best in the world.

10.1.4 Least Recently Used and Clock Algorithm

Least Recently Used (LRU) policy kicks the page with the oldest timestamp back to disk. This is done (naïvely) by timestamping each time a page is accessed. When a page needs to be replaced, we

search through all pages to kick the one with the oldest timestamp. This incurs a lot of overhead and therefore is not commonly used.

Rather, we usually use an approximate LRU, or "Clock Algorithm". We maintain a circular buffer of pages in memory, with each page having an additional reference/use bit (typically stored in the MMU). When a page is accessed, we set the reference bit to 1, indicating it has been recently used. When determining the page to replace, we scan starting at a fixed point, replacing the first page with reference bit 0.

This algorithm, while not a perfect one-to-one with LRU, offers performance on par with LRU for a fraction of the cost. Therefore, it is usually implemented in favor of a "true" LRU.

10.2 Page Replacement

We don't want to clear out *all* page frames on each context switch as it can be inefficient. There are several ways to deal with this:

(i) Single Global Pool: All processes share a single pool of page frames in memory. When a process runs, it uses any available free page frame for its page.

(ii) Fixed Allocation per Process: Each process is assigned a fixed number of page frames when it starts. The number of page frames stays constant throughout execution.

(iii) Working Set-Based Allocations: The working set of a process represents the set of pages it is actively referencing at any given time. Page frames are allocated dynamically based on a process' working set. When a process runs, its working set is loaded into RAM, and when it's switch out, its page frames are potentially freed.

10.2.1 Single Global Pool

In the Single Global Pool approach, all page frames in memory are treated as a shared resource, and an approximation of LRU is used as the replacement algorithm. However, this sucks when paired with round-robin scheduling (see **8.5.1 Round Robin**).

> **Example: Fair or Unfair**
>
> In RR scheduling, the process that was last in the queue will find all of its pages swapped out. Thus, when this process runs, it will experience a high volume of page faults since all of its pages were replaced.

This is because this approach doesn't account for the specific working sets of each process. For this reason, this approach is usually pretty dogshit.

10.2.2 Per-Process Pools

In the Per-Process Pool approach, a fixed number of pages are allocated for each process, and the approximate LRU is used *separately* for each process. This allows for dynamic and customized allocation of page frames to each process.

However, a fixed number of pages per process sucks because different processes exhibit varying levels of locality, and the pages needed by each process usually change over time. Moreover, processes have different natural scheduling intervals, and as such, their memory requirements vary throughout execution!

10.2.3 Working Sets

> **Definition: Working Set**
>
> A **working set** is defined to be the set of pages a process actively referenced within a fixed sampling interval in the immediate past.

Working sets are used to allocate page frames to each running process based on its specific memory needs. We allocate a sufficient number of page frames to hold each process' working set. This ensures that the frequency of accessed pages are kept in memory, reducing the volume of page faults. Each process will manage its own set of pages, usually using an approximate LRU for page replacement.

Working sets dynamically adjust the allocation of page frames for each process based on its current behavior, optimizing memory usage and responding to changes in workload and access patterns.

Optimal Working Sets

The optimal working set for a process is the set of pages it needs during its next time slice (or a specific period of time). Allocating less than the optimal amount leads to a lot of page faults.

We determine the size of the working set by observing the process' behavior over time. Tracking the frequency of page faults and memory references, the system can identify which pages the process frequently accesses, including them in the working set.

Page Stealing: Working Set-Clock Algorithm

The Working Set-Clock algorithm tracks the last use time for each page for its owning process, replacing the page that was least recently used.

10.3   Thrashing

> **Definition: Thrashing**
>
> **Thrashing** refers to when a system spends a significant amount of time/resources swapping pages between RAM and disk, but isn't able to efficiently make any progress in the executing process.

Thrashing occurs when the total demand for memory by *all* running processes exceeds the available physical memory. When thrashing happens, we seldom execute any useful instructions since so much time is spent swapping pages. This results in an underutilized CPU and degraded performance.

Thrashing typically happens hen the working set of each process exceeds the available physical memory. When there are not enough page frames to accommodate the working sets of all active processes, they constantly compete for memory.

To protect against thrashing, the OS takes proactive measures like reducing the degree of multi-programming (i.e. limiting the number of active processes), using page replacement algorithms that prioritize larger working sets, or allocating more physical memory (lol). The goal is to avoid thrashing by ensuring that each process has enough pages in memory to execute efficiently.

> **Example: Everyone Gets a Turn**
>
> When reducing multiprogramming, we can use a RR approach for swapping processes in and out of disk, ensuring that all processes get a fair share of CPU time while minimizing thrashing!

10.4   Clean and Dirty Pages

> **Definition: Clean and Dirty Pages**
>
> A **clean page** refers to a page in memory that hasn't been modified since it was brought from disk. They can be safely replaced without needed to write them back to disk since their contents match that of the one on disk.
>
> -
>
> A **dirty page** refers to a page in memory that has been modified or updated after it was brought from disk. That is, the in-memory version of the page is different from the one on disk. If a dirty page needs to be removed from memory, the page must be written back to disk to update the appropriate page on disk, ensuring that the most recent version of the data is saved before kicking it from memory.

When given a choice, the OS will prioritize kicking clean pages since they can be safely removed without the need for I/O. Dirty pages however, need to be written back to disk to preserve data integrity.

10.5   Preemptive Page Laundering

Preemptive page laundering is a technique used to increase the flexibility of the memory manager by converting dirty pages to clean ones. Rather than waiting to write when pages gets kicked, we initiate a background write-out of dirty pages that are not actively in use. This way, we reduce the risk of thrashing and increase the number of clean pages we have.

Part II

Concurrency

Chapter 11

Threads

> **Definition: Thread**
>
> A **thread** is a unit of execution and scheduling in a program. Each thread has its own stack, program counter, and registers, allowing it to operate independently of other threads.

Threads within the same process share the same code and data segment, making them more efficient and less resource-intensive than processes.

In multi-threaded programs, multiple threads can run concurrently within the same process. They share the process' resources (e.g. memory, files), but each thread maintains its own execution state. This allows for better communication and coordination between different parts of the program.

They can be implemented and managed in various ways. User-level threads are managed by the process itself and rely on voluntary yielding. Scheduled system threads are managed by the OS and can be preemptively scheduled, meaning the OS can interrupt it to give other threads CPU time.

> **Corollary: Why Not Processes?**
>
> Processes are expensive! Since each one has private resources and a private address space, it makes interprocess communication difficult. Additionally, certain programs may not require such strong separation. So, we can use threads to remedy such limitations of processes.

11.1 Process v. Thread

When should you use a process? A thread?

> **Processes**
>
> *(i)* Running multiple, *distinct* programs.
>
> *(ii)* Creation/destruction are *rare* events.
>
> *(iii)* Running with distinct privileges.
>
> *(iv)* Limited interactions/shared resources.
>
> *(v)* Strong separation between other processes.

> **Threads**
>
> *(i)* Parallel activities in a *single* program.
>
> *(ii)* Creation/destruction are *frequent*.
>
> *(iii)* All can run with the same privilege.
>
> *(iv)* Need to shared resources.
>
> *(v)* Frequent message/signal exchange.
>
> *(vi)* When you don't need protection from each other.

11.1.1 Tradeoffs

Processes

Advantages	Disadvantages
(i) String isolation: Processes have distinct address spaces.	*(i)* Slower communication: Interprocess communication is more complex and slower.
(ii) Fault tolerance: Processes don't affect other processes.	*(ii)* Potential duplication: Since each process has a distinct address space, this allows for unnecessary duplication.
(iii) Easier resource cleanup: When a process terminates, all resources are automatically freed.	

Threads

Advantages	Disadvantages
(i) Efficient communication: Threads share resources making communication and data sharing much faster.	*(i)* Synchronization issues: Threads must be synchronized to run properly.
(ii) Lightweight: Threads have lower overhead since they share resources.	*(ii)* Increased complexity: Multithreaded code is hard.
(iii) Faster context switching: Switching between threads is faster than switching between processes because of *(i)* and *(ii)*.	

11.2 Thread Stacks and State

Each thread has its own stack, registers, program counter, and process status. The maximum stack size for each thread is specified at creation, and needs to be managed carefully to avoid stack overflow or memory waste. Since a process can contain many threads, they cannot all grow towards a single hole. Thus, the thread creator needs to know the maximum required stack size. Moreover, stack space must be reclaimed whenever threads exit.

11.3 User v. Kernel Threads

Kernel	User
(i) Provided and managed by the OS kernel.	*(i)* Managed by the user with no intervention from the OS kernel.
(ii) Share the same address space.	*(ii)* Invisible to the kernel.
(iii) Scheduled by the kernel.	*(iii)* Scheduled by the user.

Chapter 12

Interprocess Communication

> **Definition: Interprocess Communication**
>
> **Interprocess communication (IPC)** refers to the techniques provided by the OS to enable communication and data exchange between different processes.

There are several IPC mechanisms:

(i) Pipes: A unidirectional communication channel that allows data to flow from one process to another.

(ii) Named Pipes (FIFO's): Similar to *(i)*, but can be accessed by multiple processes for bidirectional communication.

(iii) Message Queues: Allows processes to exchange messages via a system managed message queue.

(iv) Shared Memory: Allows processes to share a region of memory.

(v) Sockets: A network communication mechanism that enables processes running on different machines to communicate.

The OS supports IPC by providing system calls. They typically require activity from *both* communicating processes and are mediated by the OS for protection and to ensure correct behavior.

12.1   Goals

IPC aims to achieve:

(i) Simplicity: The mechanism should be easy to understand, use, and implement to avoid unnecessary complexities.

(ii) Convenience: It should provide a convenient interface for developers to exchange information and coordinate actions between processes.

(iii) Generality: The IPC mechanism should be flexible and versatile enough to handle various types of IPC scenarios.

(iv) Efficiency: It should be efficient in terms of time and resource usage to minimize overhead and maximize performance.

(v) Robustness and reliability: The IPC mechanism should be resilient to errors and failures, ensuring that communication is consistent and dependable.

Some of these goals are contradictory, and thus multiple different IPC mechanisms are provided to optimize for different goals.

12.2 Synchronous and Asynchronous

12.2.1 Synchronous

Both read/write operations block until the data is sent, delivered, or received, respectively. This means that the processes involved have to wait until the data exchange is complete before continuing execution. It is simple for programmers to understand but can introduce delays if processes frequently need to wait for data.

12.2.2 Asynchronous

Both read/write operations return promptly. Reads return quickly even if no new data is available. Writes return after the system accepts the data without waiting for confirmation of transmission, delivery, or reception.

Since asynchronous IPC doesn't block processes, they can continue execution, which may introduce data synchronization problems.

> **Example: 404**
>
> Assume you set up asynchronous IPC, and have process A read some data from process B. Since it's asynchronous, A won't wait for B to send everything over and will continue executing! So, it may be the case that your code starts executing instructions on data that you don't have.

To handle asynchronous operations, we need to introduce an auxiliary mechanism to learn when there's new data, often called a "wait for any of these" operation. This operation allows processes to efficiently wait for any of the asynchronous operations to complete.

12.3 Mechanics

Typical IPC operations include the following:

 (i) Create/destroy an IPC channel: These operations involve setting up and tearing down communication channels between processes. The creation of a channel allows processes to exchange data with each other, while its destruction terminates the communication link.

 (ii) Write/send/put: This operation involves inserting data into the channel, allowing a process to send information to another process. The data placed in the channel will be made available for the receiving process to read.

 (iii) Read/receive/get: The read operation extracts data from the channel, enabling a process to receive information sent by another process. The data is retrieved from the channel and made available for processing by the receiving process.

 (iv) Channel content query: This operation allows processes to check the amount of data currently present in the communication channel. This is useful to monitor the status of the channel and ensure efficient data transfer.

 (v) Connection establishment and query: Processes may require control over how their channel ends are connected to each other. These operations involve setting up and managing the connections between the two ends of the channel. Information like the identities of the end-points and the status of connections can also be queried using these operations.

12.4 Messages and Streams

Each style of data exchange are suited for particular kinds of interactions.

12.4.1 Streams

Stream-based IPC is when data flows in a continuous stream of bytes. Processes can read/write in various sizes, and the size of read/write buffers are not directly related. This gives greater flexibility in handling data of different sizes. Streams are more suitable for continuous data exchange like real-time streaming, where data arrives and is processed in an uninterrupted flow.

12.4.2 Messages

Messages (or datagrams) transmit distinct messages, each having its own length (with limitations). They are typically read/written as a whole unit; i.e. each message is treated as a separate entity. Messages are more suitable for discrete data exchanges, where separate units of data needs to be transmitted and processed independently.

12.5 Flow Control

> **Definition: Flow Control**
>
> **Flow control** is the process of regulating data transmission between a fast sender and a slow receiver so as to not overwhelm the reader with data.

In queued IPC, data is buffered n the OS until the receiver is ready to accept it. However, various factors can increase the required buffer space (e.g. fast sender, non-responsive receiver). To limit the required buffer space and ensure effective flow control, we can:

 (i) Enforce sender-side flow control: The sender can be blocked or refuse communication if the receiver's buffer is full.

 (ii) Enforce receiver-side flow control: The receiver can block the sender or flush old data if it cannot keep up.

 (iii) Implement feedback mechanisms: Network protocols or the OS can provide feedback to the sender so that it can adjust its data transmission appropriately.

12.6 Reliability and Robustness

Within a single machine, the OS ensures that data isn't lost accidentally during transmission. While on a single machine, data is never lost, it may never get processed, since the receiver could be invalid, dead, or unresponsive.

Data can get lost when communicating across a network due to network issues/failures. When this happens, we need additional mechanisms like acknowledgments and retransmission protocols to guarantee reliable data delivery.

Reliability involves determining when to acknowledge successful delivery, the level of persistence in delivery attempts, and the handling of IPC data after receiver restarts. The timing of acknowledgment can be when the message is queued locally in the sender's system, added to the receiver's input queue, or explicitly read by the receiver.

For network communication, the system may attempt multiple retransmissions and explore alternate routes or servers to ensure delivery. Whether IPC data survives receiver restarts depends on the application; some systems may allow persistence for seamless data continuation, while others may require resending messages after restarts. The choice of reliability options depends on the application's requirements and the trade-off between reliability and overhead.

12.7 Pipelines

Pipelines allow for data to flow through a series of programs, passing a simple byte stream buffered in the OS[1]. It is a straightforward and efficient way to pass data between programs.

---

[1]We don't need temporary files!

> **Example: Pipe Up!**
>
> Consider the following: `ls | grep 'CS111'`. This is an example of a pipe! the data from `ls` gets sent to the standard input of `grep`! We also implemented this in lab 1.

They are secure and *trusted*[2], but can be limiting. Error conditions include EOF and detecting failures in the programs that are part of the pipeline.

12.8   Sockets

Sockets allow IPC between addresses and ports (communication between processes on different machines). They offer various data options (e.g. reliable or best-effort), streams, messages, remote procedure calls, etc. They involve complex flow control and error handling with features such as retransmissions, timeouts, and handling node failures.

They allow for reconnection and fail-over in case of disruptions. However, this generality adds complexity such as trust, security, privacy, and integrity concerns. They are usually used for network communication due to their flexibility.

12.9   Shared Memory

Shared memory is when the operating system allows processes to share read/write memory segments that are mapped into multiple process' address spaces. The OS doesn't mediate data transfer between processes. Rather, it provides the memory segments and trusts that the applications manage sharing control.

This direct memory access allows for faster communication, but the simplicity of the approach also assumes that cooperating processes will handle synchronization and data integrity. Shared memory also only works on local machines, limiting its scope to IPC on a single device.

12.9.1   Synchronization

Synchronization is the process of coordinating and ensuring multiple events/actions occur in the correct order. This is an issue that multi-threaded applications must deal with, and can get complex. It is crucial for *parallelism*[3], and to ensure correctness in our programs.

> **Aside: Parallelism**
>
> Parallelism gives us many benefits! It lets us run multiple tasks concurrently, improving throughput. Parallelism also facilitates breaking down complex tasks into smaller, more manageable pieces, supporting modularity. When using parallelism, if one thread/process fails, it doesn't affect the others, improving robustness and isolating problems.
>
> Aside from local benefits, parallelism also support common paradigms like client-server computing, which are inherently parallel in nature. Furthermore, real-world phenomena involve the cooperative interaction of multiple processes or entities, and we can use parallelism to model these behaviors!

---

[2]They are trusted since all programs are controlled by a single user.
[3]Parallelism: Multiple threads/processes executing concurrently.

Chapter 13

Synchronization

Synchronization refers to the process of coordinating the execution of multiple concurrent threads/processes to ensure orderly and predictable behavior in a parallel system. It involves two interdependent subproblems: the critical section serialization and the notification of asynchronous completion.

While true parallelism can be complex and difficult to understand, many systems employ pseudo-parallelism, where the focus is on controlling and coordinating key points of interaction rather than attempting a truly parallel execution. Synchronization mechanisms often address both problems simultaneously, as solving one implicitly addresses the other. However, understanding and solving critical section serialization and notification of asynchronous completion can be solved separately to manage the complexities of parallel systems effectively.

13.1 Race Conditions

Race conditions occur when the outcome of a program depends on the order in which concurrent threads/processes run. As such, they can affect the correctness of a given program.

> **Example: No I Wrote First!**
>
> A race condition can happen when we read and write to the same piece of data from different threads (that aren't synchronized). `counter = counter + 1` is a great example! Who knows *when* each thread will increment `counter`, and which value they'll go off of? No one!

We employ strategies like mutual exclusion, synchronization, and transactions to try and mitigate race conditions in concurrent systems.

> **Corollary: Nondeterminism**
>
> Nondeterministic execution is more general than race conditions, and refer to *any* execution that make behavior less predictable.
>
> > **Example: I/O**
> >
> > Suppose you write code that takes in input. When your program waits for a read from your keyboard, the time it takes to read the data may vary drastically, depending on how dumb your user is! This makes I/O inherently nondeterministic.
>
> Addressing these issues requires careful synchronization and coordination mechanisms.

13.2 The Critical Section

> **Definition: Critical Section**
>
> A *critical section* is a code segment where shared resources are accessed and modified. Naturally, it must not be accessed simultaneously by more than one entity to avoid race conditions and other synchronization issues.

The state of the shared can be altered by the critical section, including changes to its contents or relationships with other resources. Therefore, it is crucial to control access to it to avoid conflicts and preserve the integrity of the shared resource.

Correctness depends on the execution order of the threads/processes/CPU's, which is influenced by the scheduler. Additionally, the relative timing of asynchronous and independent events can also impact the behavior of critical sections and therefore the overall system. Managing critical sections involves coordinating the access to the shared resource to prevent undesirable interleavings

13.3 Interrupt Disables

One solution to the critical section problem is to use interrupt disables, which temporarily block some or all interrupts! By temporarily blocking some or all interrupts, we can ensure that there will be no preemption by interrupt handlers (or threads) during a critical section.

Interrupt disables have a multitude of abilities and dangers. On the bright side, they prevent time-slice interrupts and avoid re-entry of device driver code, ensuring that the critical section is executed without interruption. However, some risks of disabling interrupts can include delaying important operations (like preemptive scheduling) or being permanently disabled due to a bug. Additionally, disabling interrupts isn't an option in user mode, and requires the use of privileged instructions (for safety purposes). It is worth noting that they don't solve *all* synchronization problems, especially on multi-core machines.

13.4 Mutual Exclusion

> **Definition: Mutual Exclusion**
>
> **Mutual exclusion** ensures that only one thread can execute a critical section at a time. To ensure proper synchronization, we need to enforce mutual exclusion; i.e. if one thread is running the critical section, the other definitely isn't.

13.4.1 Atomicity

> **Definition: Atomicity**
>
> **Atomicity** is defined by two aspects: "Before or After" and "All or None".
>
> (i) Before or After: Given two threads A and B, if A enters the critical section *before* B starts, B will enter the critical section *after* A completes (and vice versa). That is, there is *no* overlap between threads.
>
> (ii) All or None: Updates within the critical section are performed entirely or not at all. If an update starts, it will either complete successfully and apply changes or revert back to its original state (before the critical section).

Achieving both aspects of atomicity is essential for correctness and consistency.

13.4.2 Locking

Locking is a technique used to protect critical sections. It involves a data structure called a "lock" which serves as a synchronization mechanism.

When a thread wants access to a critical section, it will attempt to acquire the lock associated with it. If it's available, the thread locks it and can access the critical section. Otherwise, the thread must wait (e.g. blocked, suspended) until the lock becomes available.

Locks ensure that only one thread can hold a lock at any time, enforcing mutual exclusion and preventing multiple threads from simultaneously accessing a critical section. Proper use of locks avoid race conditions and maintain correctness of parallel programs. However, they have their separate issues like deadlocks and lock contention.

Implementing Locks

Unfortunately, ISA's usually don't include instructions for building locks, so we need to build locks in software. However, this raises other issues of enforcing *their* mutual exclusion. Luckily, we can solve these issues with hardware assistance!

Individual CPU instructions are atomic, so we want to implement a lock with a *single* instruction! Remember, acquiring a lock requires that we:

(i) Check no one else has it.

(ii) Change the lock to "acquired".

Lucky for us, hardware designers have solutions for that!

Example: Test and Set

Below is a *representation* of how locks are implemented. Remember, the *real* instructions are silicon, not in C!

```c
bool test_and_set(char *p) {
  bool rc;
  rc = *p;   // note the current value
  *p = true; // set the value to true (i.e. acquired)
  return rc; // return the OLD value
}
```

Now, when we evaluate `if !test_and_set(flag)`, we know that if `rc` was false, no one else ran it, so we can acquire the lock! If `rc` was true, then someone else already ran it, so they have the lock.

Corollary: Spin Waiting

When you don't get the lock, you can do something known as *spin waiting*! Essentially, you put the lock request in a while loop until you get the lock.

Advantages

(i) It properly enforces access to critical sections! This also assumes you implemented locks properly.

(ii) They're simple to program. I mean it's usually just a while loop.

Disadvantages

(i) It's wasteful. Spinning uses CPU cycles which is inefficient!

(ii) The cycles burned could be used by the locking party to finish its work!

(iii) Bugs can lead to infinite spin-waits.

13.5   Asynchronous Completion

The asynchronous completion problem occurs when parallel activities run at different speeds, and one activity needs ton wait for the other to complete without hindering performance. examples include I/O, network request responses, or real-time delays.

13.5.1   Spinning

Spinning sometimes makes sense:

(i) When the operation proceeds in parallel, such as a hardware device accepting a command or another core quickly releasing a held spin lock.

(ii) When the operation is guaranteed to happen soon, spinning can be less expensive than using sleep/wakeup mechanism.

(iii) When spinning does not significantly delay the operation or impact system resources, like when burning CPU cycles does not hinder other processes or slow I/O operations due to memory bandwidth.

(iv) When contention for the resource is expected to be rare, as having multiple waiters for the same resource could substantially increase overhead and inefficiencies.

13.5.2   Yield and Spin

Yield and Spin is a technique where a thread repeatedly checks if a particular event has occurred, yielding the CPU if it hasn't. The thread keeps checking and yielding until the event is ready. This approach avoid busy-waiting, maximizing useful CPU time.

Problems

Some problems of Yield and Spin include:

(i) Extra Context Switches: Frequent yielding and spinning can lead to additional context switches, which are expensive operations and can impact overall system performance.

(ii) Wasted Cycles: If a process spins every time it is scheduled, it can waste CPU cycles, especially if the event it is waiting for doesn't occur in the expected timeframe.

(iii) Delayed Scheduling: There's no guarantee that a process will be scheduled to check for the event in a timely manner, potentially causing delays in responding to the event.

(iv) Poor Performance with Multiple Waiters: When multiple processes are waiting for the same event, the Yield and Spin approach can result in unfairness, where some processes are repeatedly scheduled and others are not, leading to an inefficient use of resources.

13.5.3   Completion Events

Completion events provide a more efficient approach for synchronization compared to spinlocks or busy waiting. Instead of repeatedly checking for the availability of a lock or resource, a thread or process that cannot acquire the lock can choose to block and be notified later when the lock becomes available.

This mechanism is also applicable to situations where a process needs to wait for other processes or I/O operations to complete before proceeding further.

> **Example: What to Do?**
>
> A thread can wait for an I/O operation to finish, or another process to complete its task, without wasting CPU cycles.

These completion events are implemented using condition variables provided by the operating system, which allow threads to block efficiently and wake up only when the desired condition is met, thus avoiding unnecessary context switches and improving overall system performance.

13.5.4   Condition Variables

Condition variables allow threads to block and wait for a specific even or state change before proceeding. When the desired condition is met, another thread signals the condition variable which unblocks the waiting threads and allows them to continue execution.

Condition variables are usually provided by the OS or implemented in thread libraries. When a thread waits on a condition variable, it's blocked and removed from the ready queue. The OS or thread library then monitors the variable and unblocks the waiting thread(s) when the desired event occurs, placing it back on the ready queue (or possibly preempting the current thread).

> **Corollary: Multiple Waits**
>
> Threads can wait on several different things, so we want to wake threads up only when they *should*. So, the OS or thread library should allow easy selection of the correct thread(s) to wake up. Usually, we use a waiting queue to handle multiple waits.

13.5.5   Waiting Lists

Rather than spinning for a lock, we often use waiting lists, a shared data structure that keeps track of threads waiting for a particular lock. However, this implementation may have circular dependencies (which should be avoided!): since the waiting list itself is shared, we should probably put a lock on it to prevent concurrent access.

> **Example: Sleeping Beauty**
>
> Suppose thread B locks a resource that thread A wants to use. So, thread A will call `sleep()` to wait for the lock to be free. At the same time, thread B finishes and calls `wakeup()` to release the lock. Assuming no other threads are waiting for the resource, we have a race condition! `wakeup()` may potentially have no immediate effect (since there's no one waiting for the resource), and thread A might sleep indefinitely.

The example above illustrates an example of *deadlock*[1]. Fortunately, this is a mutual exclusion problem! `sleep()` is the *critical section* that we need to handle. We need to prevent `wakeup()` and other people from joining the waiting list.

> **Corollary: Fairness**
>
> Fairness in the context of mutual exclusion refers to the guarantee that all processes, threads, or machines requiring access to a resource will eventually be granted access. The goal is to prevent starvation, where some processes are consistently denied access while others frequently obtain it.
>
> Achieving fairness in locking mechanisms can be challenging and depends on the choice of approach. For instance, using First-In-First-Out (FIFO) locks ensures that access is granted based on the order of arrival, enforcing fairness in request sequence.
>
> Additionally, priority inversion avoidance techniques can be employed in systems with priority levels assigned to processes. Implementing yielding in spinlocks can also promote fairness by allowing other processes to make progress while a lock is held.
>
> Advanced locking techniques like ticket locks or MCS locks inherently provide fairness properties by ensuring waiting processes are granted access in a fair manner. Although achieving perfect fairness in all scenarios might not always be feasible, considering fairness in the design of the system can help maintain equitable resource access among multiple contenders.

---

[1]Deadlock refers to the situation where a set of threads are unable to proceed with execution because they're waiting for a resource that is held by another process in the set. Consequently, all processes in the set wait indefinitely.

Chapter 14

Synchronization Primitives

Synchronization primitives are tools to manage the concurrent execution of multi-threaded programs. They help prevent race conditions and ensure that shared resources are accessed in a controlled and safe manner. They provide mechanisms for controlling the order of execution, ensuring data consistency, and preventing any race conditions.

14.1 Semaphores

> **Definition: Semaphores**
>
> **Semaphores** are a synchronization mechanism that controls access to shared resources and manages concurrent execution of multiple processes or threads.

While semaphores are *theoretically* well-defined, they are not always the most practical choice for real-world synchronization primitives, since there are gaps between theory and *practical* implementation; i.e. some abstract concepts of semaphores may not directly translate to intuitive solutions in real code.

> **Corollary: Computational Semaphores**
>
> Computational semaphores are *the* classic synchronization mechanism[a] as its behavior is well-defined and is the foundation for most synchronization studies. They are more powerful than simple locks, providing a richer set of features. For the rest of this section, when we refer to semaphores, we are referring to **computational semaphores**.
>
> > **Example: Waiting in Line**
> >
> > Semaphores incorporate a FIFO waiting queue, ensuring that *all* processes/threads are granted access in the order they requested it, avoiding potential issues like starvation. Additionally, unlike binary flags used in simple locks, computational semaphores use a (modifiable) counter to manage access to allow a limited number of concurrent access to a critical section.
>
> ---
> [a]Computational semaphores were introduced by Edsger Dijkstra in 1968.

14.1.1 Structure

A semaphore consists of two primary components: the *integer counter* and *FIFO waiting queue*. The integer counter represents the current state of the semaphore and manages access to a critical section. The FIFO waiting queue manages which order the threads are granted access to the critical section.

Aside: Why Semaphores Don't Broadcast

Semaphores, in their basic form, don't provide a built-in mechanism to broadcast because they weren't designed to. They are designed to control access to a critical section by limiting the number of threads that can access the resource simultaneously rather than manage communication between multiple threads.

14.1.2 Operations

There are two operations: *Proberen* and *Verhogen.*

P (Proberen/Test)

The P operation[1] is used when a thread wants to access a critical section protected by a semaphore. Its steps are as follows:

(i) Decrement the *integer counter.*

(ii) If the resulting value is non-negative ($0 \leq$), the thread is allowed to proceed, and enters the critical section.

(iii) If the resulting value is negative (< 0), the resource is currently unavailable, so the thread is added to the waiting queue.

V (Verhogen/Raise)

The V operation[2] is used to release the semaphore and *signal* that the shared resource is now available for use. Its steps are as follows:

(i) Increment the *integer counter.*

(ii) If the waiting queue is non-empty, wake up one of the waiting threads and allow it to enter the critical section.

These operations ensure that threads interact with the shared resource in a coordinated and controlled manner. The P operation enforces mutual exclusion by allowing only one thread access at a time, while the V operation ensures that there is no resource starvation by allowing *everyone* to *eventually* access the critical section via the *FIFO waiting queue.*

14.1.3 Use Cases

Example: Exclusion

Semaphores can be used to ensure exclusion: only one thread can access a critical section of code at a time, preventing data corruption.
We can do this by doing the following:

(i) Initialize the *integer counter* to 1^a.

(ii) When a thread wants to take a lock, use *P/wait.* Here, the first *wait* will succeed (counter $= 0$). Any subsequent *wait*'s will block (counter $= -1$).

(iii) When a thread is done and wants to release the lock, use *V/signal.* Now, counter $= 0$, and if there are any waiting threads, unblock the first one. This thread will now take the lock.

---

^{a}The integer counter reflects the number of threads allowed to hold the lock on a critical section. Initializing the counter to 1 ensures mutual exclusion!

---

[1] Also known as "wait".
[2] Also known as "signal".

14.1.4   Limitations

While semaphores are a fundamental synchronization mechanism, they have certain limitations which impacts their overall usability and practicality.

(i) Too *Basic*: Semaphores are considered a basic mechanism for synchronization. They were designed to be simple tools that could be used in mathematical proofs to demonstrate the correctness of concurrent algorithms.

(ii) Limited Features: Because they were designed to be simple tools for theoretical analysis, they are ill-fitted for practical synchronization in real-world symptoms.

(iii) Deadlocks and Blocking: It is relatively easy to unintentionally create deadlocks with semaphores. Moreover, we cannot check if a lock is available without potentially blocking if it's not.

(iv) Shared Access: Semaphores don't inherently support complex synchronization scenarios such as read/write shared access[3].

(v) Recovery: If a process crashes or becomes unresponsive while holding a semaphore, the semaphore can become "wedged", where it cannot use *V/signal* to resolve itself.

---
[3] In read/write shared access, multiple readers can access a shared resource, but exclusive access is needed for writers.

(vi) Priority Inheritance: Semaphores don't address priority inversion issues, where lower-priority tasks can block higher priority ones.

Despite these limitations, semaphores are widely supported and used in most operating systems and concurrent programming environments. They serve as a fundamental synchronization tool due to their simplicity.

14.2 Mutexes

> **Definition: Mutex**
>
> A **mutex** is a synchronization mechanism used in (mostly) Unix/Linux environments to provide mutual exclusion and lock sections of code, ensuring only one thread can access a critical section at any given moment.

Mutexes are designed to lock (typically) small and critical sections of code, implying that these locks are expected to be held *briefly*[4]. They are typically used for multiple threads[5] of the same process and have low overhead and are very general.

14.2.1 Object Locking

Recall that mutexes only protect critical sections of *code*. To protect persistent *objects*, we want to lock the objects themselves. Object locks are more versatile than code-level locking since they can protect resources that persist beyond the lifetime of a program's execution (e.g. a file) and offer adjustable *granularity*[6].

Though object-level locking provides mutual exclusion, it can bottleneck performance and limit the scalability of a project (via excessive locking). Furthermore, object locks can potentially cause deadlocks. Thus, object-level locking is very specific, as we need to carefully work with the concurrency requirements and choose an appropriate granularity to ensure effective and efficient locking mechanisms.

---

[4]Locks are expected to be held briefly *relative* to the program.

[5]Mutexes are *assumed* to be used for threads operating on shared data; i.e. all threads are operating in a single address space. This implies that mutexes (protecting *code*) won't work for multi-process programs

[6]Granularity: We may want to either lock an entire object at a time or lock specific methods or sections *within* the object.

Corollary: Advisory v. Enforced Locking

Definition: Advisory and Enforced Locking

Advisory locking[a] is a locking mechanism that is *purely suggested* by the application. It relies on developers respecting the locking protocols being used and are *non-blocking*[b]. Mutexes and `flock()`'s are examples of advisory locks.

---
[a]Also known as: user-level or application-level locking.
[b]Non-blocking: Advisory locks do *not* automatically block threads that attempt to access a locked resource. Thus, it is the application's responsibility to check and handle locks.

- -

Enforced locking[a] is a locking mechanism that is *strictly enforced* by the OS or underlying system infrastructure. It is typically used when data integrity is crucial. They are done within the implementation of object methods and are guaranteed to happen[b].

---
[a]Also known as: mandatory or kernel-level locking.
[b]Blocking: Enforced locks will automatically block threads that attempt to access a locked resource, enforcing mutual exclusion.

We will take a look at an example of an *advisory* lock and an *enforced*[a] lock.

Example: A `flock` of Seagulls

Let's take a look at Linux's file descriptor locking: `int flock(fd, operation)`. Supported operations include:

(i) `LOCK_SH`(ared): Place a *shared* lock on `fd`. More than one process may hold a shared lock for a given `fd` at a given time.

(ii) `LOCK_EX`(clusive): Place an *exclusive* lock. Here, only one process may hold an exclusive lock for a given `fd` at a given time.

(iii) `LOCK_UN`(nlock): Remove an existing lock held by the calling process.

This lock applies to *open* instances of the same `fd`. Note that *distinct* opens are *not* affected. Moreover, these locks are *advisory* and not strictly enforced.

Example: A `lockf` of eagullsS

Let's look at the Linux ranged file lock: `int lockf(fd, cmd, offset, len)`. Supported commands include:

(i) `F_LOCK`: Set an *exclusive* lock on the specified section of the file. If (part of) this section is already locked, the call *blocks* until the previous lock is released. If this section overlaps an earlier locked section, both are merged. File locks are released as soon as the process holding the locks closes some `fd` for the file. Note that a child process does *not* inherit these locks.

(ii) `F_TLOCK`: Same as *(i)*, but the call *never* blocks. Instead, we return an error if the file is already locked.

(iii) `F_ULOCK`: Unlock the indicated section of the file. This may split a single locked section into two locked sections.

(iv) `F_TEST`: Test the lock: returns 0 if the specified section is un/locked by this process; returns -1 and sets `errno = EAGAIN/EACCES` if another process holds a lock.

This lock applies to the *file*, not its open instance. Thus, this lock is process specific and closing *any* `fd` for the file releases for *all* of the process' `fd`'s for that file. Depending on the underlying system, these locks are *enforced*.

---
[a]Whether or not `lockf` is enforced depends on the underlying file system.

14.3 Locking Problems

We will talk about two main problems related to locking: performance/overhead and contention.

14.3.1 Performance and Overhead

Locking mechanisms are usually implemented as syscalls, incurring traditional syscall overheads[7]. When locking operations are called frequently (e.g. a *heavily* threaded application, the cumulative overhead of the syscalls may become significant enough to notice, leading to contention and degraded performance, reducing overall efficiency.

Enforced locks often incur more overhead than advisory locks since the OS needs to manage and coordinate access to the locked resource among multiple threads/processes. However, even if locking isn't enforced or is implemented outside of the OS, we still need to execute extra instructions to lock and unlock.

The granularity of locks can also impact performance. *Fine-grained locks*[8] can reduce contention but may incur overhead, since we un/lock more frequently. *Course-grained locks*[9] can reduce overhead but may result in more contention among threads/processes.

Unfortunately, locking code in operating systems have already been highly optimized, thus there is not much more that can be done.

> **Aside: Locking Costs**
>
> Locking is typically used when we need to protect critical sections to ensure correctness. Since many critical sections are very brief (e.g. in/out in nano-seconds), the overhead of the locking operations may be much higher than the time spent in the critical section. This is why we care about locking overheads!

14.3.2 Contention

When a thread doesn't get a lock, we block! However, blocking introduces significant overhead compared to simply acquiring a lock, and the cost can vary depending on the likelihood of contention.

> **Definition: Contention**
>
> **Contention** refers to when multiple threads/processes are competing for access to a shared resource.

The expected cost of acquiring a lock, taking into account the probability of contention, is defined as:

$$C_{expected} = (C_{block} \cdot P_{conflict}) + (C_{get} \cdot (1 - P_{conflict}))$$

where

(i) $C_{expected}$ is the expected cost of acquiring a lock.

(ii) C_{block} is the cost associated with a thread being blocked due to contention. This include the overhead of context switches, potential queuing, and any other blocking costs.

(iii) C_{get} is the cost associated with successfully acquiring the lock without contention. Typically, this cost is lower than *(ii)*.

(iv) $P_{conflict}$ is the probability of a contention occurring.

$(C_{block} \cdot P_{conflict})$ represents the cost when there is contention, while $(C_{get} \cdot (1 - P_{conflict}))$ represents the cost when there is no contention (i.e. acquires the lock without blocking). Considering both scenarios and their costs, this formula provides an estimation of the overall expected cost of acquiring the lock.

---

[7]If locking operations are performed frequently, we may incur high overhead since it is essentially calling syscalls frequently.

[8]Fine-grained: Locks that protect small sections of code.

[9]Course-grained: Locks that protect larger sections of code.

14.3.3 Reducing Contention

There are many solutions to reduce contention. Here, we will cover the following:

(i) Eliminate the critical section entirely.

(ii) Eliminate preemption during critical sections.

(iii) Reduce the time spent in critical sections.

(iv) Reduce the frequency of entering critical sections.

(v) Reduce *exclusive* use of serialized resources.

(vi) Spread requests out over more resources.

Eliminating Critical Sections

We can solve the contention problem by simply eliminating the source of contention: critical sections. In this approach, we eliminate shared resources entirely, giving everyone their own copy. Additionally, we use atomic instructions wherever possible. This approach is great when feasible, but we often cannot simply avoid critical sections.

Eliminating Preemption in Critical Sections

In this approach, we do not allow preemption when inside of a critical section. If critical sections cannot be preempted, we eliminate synchronization problems! However, this usually involves disabling interrupts and is not always viable.

Reducing Time Spent in Critical Sections

Here, we move potentially blocking operations[10] outside of critical sections and minimize the code inside the critical section. We want to include only code that is subject to destructive races. Unfortunately, while this approach is intuitive, it may complicate the code, unnaturally separating parts of a single operation.

Reducing the Frequency of Entering Critical Sections

This approach involves minimizing the number of times threads/processes need to access shared resources or critical sections. We achieve this by simply using high-contention resources/operations less often by either optimizing our algorithms to reduce the reliance on them or simply use them less. Additionally, we can perform batch operations rather than executing individual operations one by one.

In some scenarios, we can employ *sloppy counters*. Here, each thread maintains and updates a private counter as opposed to the shared global counter. This however implies that the global counter is not always up-to-date. Additionally, thread failure can lose updates if it hasn't written to the global. Alternatively we can sum single-writer private counters when we need to access the global counter.

Remove Exclusivity Requirements

We want to reduce the amount of resources that require *exclusive* access. For example, in read/write locks, only *writers* require exclusive access. Thus, we allow many *readers* to access the shared resource, only enforcing exclusivity when *writing*[11].

Spread Requests Over More Resources

This approach changes the lock granularity (See **14.3.1 Performance and Overhead**) to reduce contention. Coarse-grained locks are simpler and more idiot-proof, but increase resource contention. Fine-grained locks spread activity over many locks to reduce contention, but increase overhead.

---

[10]Potentially blocking operations include (but are not limited to): allocating memory, I/O, etc.

[11]This requires a new policy: how do we determine when writers are allowed in? A bad policy can lead to potential starvation if writers must wait for readers.

14.3.4   The Convoy Effect

> **Definition: Convoy Effect**
>
> The **convoy effect** refers to the scenario where multiple threads/processes are blocked while waiting for access to a single shared resource. These threads/processes form a queue or *convoy*, with each one waiting for the resource to become available.

  While the convoy is waiting for the resource, no other work can be done. This means that parallelism is effectively eliminated during the time the convoy is waiting, since even if there are other unrelated tasks that *could* run in parallel, they are delayed due to the resource contention. Since processes are waiting in line, they are *forced* to execute in a sequential manner. Process $i + 1$ can only proceed after process i releases the resource. This causes the resource to be a bottleneck in the system; that is, the overall system performance is limited by the speed at which the resource can be accessed and released. Thus, the system's throughput and efficiency can be severely compromised.

  In a FIFO queue formation[12], the formula to estimate the probability of contention is defined as

$$P_{conflict} = 1 - \left(1 - \frac{T_{wait} + T_{critical}}{T_{total}} \right)^{threads}$$

where

  (i) $P_{conflict}$ is the probability of contention.

 (ii) T_{wait} is the time spent waiting for the resource.

(iii) $T_{critical}$ is the time spent actively using the resource in a critical section, where it has exclusive access.

(iv) T_{total} is the total time a thread takes to complete its execution, including both the time spent waiting(*(ii)*) and the time spent using the resource (*(iii)*).

 (v) *threads* is the number of threads.

In the general case[13], we get

$$P_{conflict} = 1 - \left(1 - \frac{T_{critical}}{T_{total}} \right)^{threads}$$

  In both cases, as contention increases, the probability of contention increases. If T_{wait} becomes *long enough*[14], newcomers joining the queue can make the wait time even longer, potentially ceasing parallelism.

---

[12]FIFO formation happens when threads wait in line to access the resource.
[13]The general case assumes there is no FIFO queue formation.
[14]T_{wait} reaches teh mean inter-arrival time.
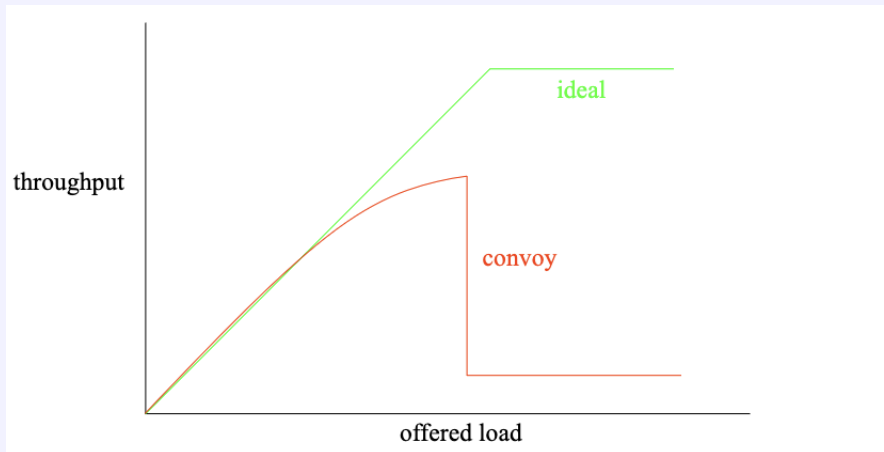
Here we see the graph illustrating the convoy effect. The inflection point of the convoy line represents the system bottlenecking due to a high T_{wait}.

14.4 Priority Inversion

Definition: Priority Inversion

Priority inversion refers to a situation in priority-based scheduling systems using locks where a higher-priority process is blocked and delayed by a lower-priority process that currently has a lock on the desired resource. This effectively reduces the higher-priority process to the lower-priority process.

Priority inversion can lead to reduced performance, since the program may be bottlenecked by the lowest-priority process. This leads to an inefficient utilization of resources and increases the risk of deadlock, especially with intermediate priorities[15]. Moreover, the program becomes unpredictable and has the potential to cause system crashes.

Example: Get on my Level

Suppose we have two processes, L (low-priority) and H (high-priority) and a mutex M. Say L is holding M and is preempted since H has higher priority and is ready to run. However, H blocks for M since L is currently holding it! This reduces H's priority to L's priority.

14.4.1 Priority Inheritance

A common solution to the priority inversion problem is *priority inheritance*. It involves temporarily raising the priority of the lower-priority task, L, (holding the lock) to that of the highest-priority task waiting for the locked resource, H. This prevents L from being preempted by a higher priority task waiting on the locked resource. Once the resource is released, the priority of L is reduced to its original value.

---

[15]Intermediate priorities may lead to a cyclic dependency which will cause a deadlock scenario.

14.5 Deadlocks

> **Definition: Deadlock**
>
> A **deadlock** is a situation where two entities are unable to proceed with execution because they are each waiting for the resource that the other entity holds.

Understanding deadlocks are important for a myriad of reasons. They pose a major risk in complex applications since they can lead to system failures. Moreover, they are usually hard to detect and their occurrence is usually nondeterministic. Hence, it is usually commonplace to prevent the possibility of deadlocks at design time.

> **Example: The Dining Philosophers Problem**
>
> Suppose there are 5 philosophers at a table along with 5 plates of pasta and 5 forks. Each philosopher needs two forks to eat pasta, but must pick them up one at a time. Assume that the philosophers will not negotiate with one another and they may try to eat at any given moment. Given these constraints, we see a potential deadlock.
> If all 5 philosophers attempt to eat at the same time, each grabs one fork. Since the philosophers do not negotiate with each other, they wait on another philosopher to relinquish a fork. However, since all 5 philosophers are waiting, we see that none of the philosophers will eat, leading to deadlock!

Deadlocks are usually hard to detect since process' resource needs are constantly changing, as they depend on what data they are operating on, where in computation they are, and what errors have occurred. Additionally, modern software usually relies on many *independent*[16] *services*[17] that each requires a variety of resources.

14.5.1 Resource Types

> **Definition: Commodity and General Resources**
>
> **Commodity resources** are ones that are given to processes in *quantities*. They are usually shareable among processes and can be divided/allocated as needed.
>
> -
>
> **General (serially reusable) resources** are ones where processes require exclusive access to a particular instance.

> **Example: Commitment Issues (Over-commitment)**
>
> Suppose you have a system with 8 GB of physical memory and a Virtual Machine that allocates a total of 16 GB of virtual memory to 4 *VM's*[a]. So, each VM thinks it has 4 GB of memory. Now assume that all VM's start using their allocated memory extensively. As they begin to exceed the amount of physical memory available, potential deadlocks can arise if the resource manager is not careful.
>
> ---
> [a]In this example, VM will refer to Virtual Machines.

---

[16]Independent: Services need not be aware of others' existence.

[17]Services encapsulate a *lot* of complexity, and as such, we don't know what resources they require nor do we know when/how they are serialized.

> **Example: Cyclic Dependencies**
>
> Suppose there are two processes A and B and two semaphores X and Y. Now, assume A acquires X and B acquires Y. A deadlock happens when:
>
> *(i)* A tries to acquire Y but is blocked since it's being held by B.
>
> *(ii)* B tries to acquire X but is blocked since it's being held by A.
>
> So, we have that A and B are both waiting on each other, forming a cyclic dependence. These types of deadlocks are usually prevented at design time.

14.5.2 Deadlock Conditions

For a deadlock to occur, *all* four conditions *must* be met:

(i) Mutual exclusion

(ii) Incremental allocation

(iii) No preemption

(iv) Circular waiting

Condition I: Mutual Exclusion

The resource in question *must* be one that requires exclusive access; i.e. once a resource has been given to a process, *all* other requesting processes *must* wait. Otherwise, we wouldn't have deadlock since we can just give an instance of the resource to all the requesting processes.

Condition II: Incremental Allocation

Entities are allowed to ask for resources at any time rather than requesting them before execution. Otherwise, they either get everything they need and run to completion or don't get everything they need and abort execution. In either case, we don't get deadlock.

Condition III: No Preemption

When an entity has access to a resource, we cannot preempt it; i.e. once an entity has access to a resource, we must wait for it to free the resource. Otherwise, we can resolve all deadlocks by preempting the offending process(es).

Condition IV: Circular Waiting

We *must* have a situation that causes a circular wait; i.e. we have a cycle in a graph of resource requests. Otherwise, there is no cycle, so *someone* can complete without anyone releasing a resource. This allows even a long chain of dependencies to *eventually*[18] unwind.

14.5.3 Avoiding Deadlock: The Reservation System

Note how we said in the previous section that *all* four conditions must be met for a deadlock to arise. However, that is much easier said than done. We can, however, use methods that guarantee that no deadlock can occur by nature. We introduce the notion of *reservations*.

In the reservation system, the resource manager tracks outstanding reservations requested by processes. Rather than fulfilling any and all requests, we only honor reservations if and only if the resources are truly available. This prevents situations where too many tasks expect resources that aren't there (over-commitment), detecting over-subscriptions early.

---

[18]We promise that it eventually unwinds, not that it unwinds quickly.

In the reservation system, we may run into resource starvation. Because reservations are only honored if the resource is available, some processes may never receive the resources they reserved. While this leads to resource scarcity, it does *not* lead to a deadlock! This allows us to handle this scarcity in a *controlled* way.

We clearly face a dilemma: should the resource manager over-commit or under-utilize? Striking a balance is key to maintain optimal resource utilization without risking critical resource shortages.

Handling Reservations

Entities seldom require *all* available resources at all times. As a corollary, we extrapolate that all clients don't need their maximum allocated resources simultaneously. This raises the question: Can we *safely* over-book resources.

> **Example: Fly Fucked**
>
> Airplanes often over-book on every flight, banking on people not showing up. Fortunately for them, they are often correct! Can we apply the same concept to operating systems?

Let's define what a safe allocation is:

> **Definition: Safe Allocation**
>
> A **safe allocation** is one where everyone can *eventually*[a] complete their tasks. That is, we ensure that no deadlocks!
>
> ---
> [a]Again, we only promise that all entities eventually complete, not that they complete in a swift manner.

> **Corollary: Commodity Resource Management in Real Systems**
>
> Many real-world systems use advanced reservations to manage resource efficiently. In these systems, one a reservation is accepted, the system is obligated to honor it. This way, we prevent resource starvation since allocation failures only occur at the time of reservation, usually before the start of execution. This makes system behavior more predictable and easier to handle. This also forces the client to deal with the reservation failure, meaning we don't have to!

14.5.4   Reservation Failures

While reservations eliminate deadlock, applications still need to deal with reservation failures. We should design applications to handle failures *gracefully*[19]. Additionally, we need to be able to communicate to the requester that a reservation failed (e.g. error messages or return codes). Finally, the application *must* be able to continue running. Naturally, this forces all critical resources to be reserved prior to execution.

While rejecting requests are not ideal, they are better than system failure later down the road. This way, the advanced notice allows applications to adjust their services to work without the unavailable resource. If the application is in the process of fulfilling a request and the resource becomes unavailable, complications arise. At this point, if a failure occurs, we need to roll back the actions that have already taken. This process can be complex or even impossible depending on the situation.

---
[19]For example, we can refuse to perform a new request, but continue running.

Consider a web server that relies on a database. If the database becomes temporarily inaccessible (e.g. maintenance or network issues), we can adjust our services to display a cached version of the web page or show an error message instead of crashing entirely! We can do this by implementing mechanisms like graceful degradation. Let's look at an example of a situation where a reservation is rejected in the middle of fulfilling a request. Suppose we have a shopping application is processing a customer's order, and the payment gateway becomes inaccessible between deducting funds and confirming the order. Here, we need to refund the money which would be a nontrivial task.

14.5.5 Avoiding Deadlock: Additional Measures

Deadlock prevention focuses on ensuring that a specific lock doesn't lead to deadlock by addressing one of the four deadlock conditions (See **14.5.2 Deadlock Conditions**). Remember, if *any* of the four conditions are not met, we don't have deadlock! Let's take a look at how we can prevent deadlock by failing to satisfy each of the four conditions.

Condition I: Mutual Exclusion

We can prevent deadlock by utilizing shared and private resources. Recall that deadlocks cannot occur over shareable resources, which are typically managed using atomic instructions. Like shareable resources, deadlock cannot occur over private resources since they are owned by individual processes!

Condition II: Incremental Allocation

To combat deadlock, we can allocate all our resources in a single operation as well as use non-blocking requests. Here, if we cannot allocate everything, we return failure and don't lock, proceeding otherwise. Note that in this approach, we get an all or nothing allocation. Non-blocking requests will fail if the request cannot be satisfied immediately. Finally, we can disallow blocking while holding resources. That is, we must release all held locks before blocking, reacquiring them *after* you return[20].

Condition III: No Preemption

We can implement resource confiscation to combat deadlocks. Here, we seize and reallocate resources from existing processes. We achieve this via resource "leases", with time-outs and "lock breaking"[21]. This approach requires us to enforce resource revocation. We can do this by either invalidating resource ownership *(i)* or terminating the previous owner *(ii)*. To achieve *(i)*, when a resource is taken away from a process, the ownership of that resource is invalidated. Thus, the process loses access to the resource and prevents it from attempting to use a confiscated resource! To achieve *(ii)*, we simply terminate the previous owner. This option is usually a last resort and is only used when resource invalidation is not possible[22].

The operating system can only seize a resource if the process has to use a system service to access the resource. If the process has direct access to the object (e.g. the object is part of the process' address space), then we're fucked and usually have to resort to terminating the process to free the resource.

---

[20]It is important to note that while this approach may solve the deadlock problem, it can introduce new ones. Remember, CS is all about give and take!

[21]Lock breaking: When a process' "lease" is up, the resource is automatically taken away and returned to the resource pool.

[22]Like Condition II, lock breaking may fix deadlock but can damage resources!

Condition IV: Circular Waiting

We can enforce *total resource ordering*. Here, all processes requesting resources follow the same order when allocating them. Given two resources R_1 and R_2, *all* processes are *required* to allocate R_1 before attempting to allocate R_2. This way, we prevent circular dependencies by creating a DAG[23]! To implement total resource ordering, we need to order the resources! We can do this by ordering them by resource type (e.g. groups before members) or by relationship (e.g. parents before children).

> **Aside: The Lock Dance**
>
> Suppose two process (P_1 and P_2) needs to allocate resources (R_1 and R_2) out of order. Initially, we have $P_1 : R_1$ and $P_2 : R_2$, but our desired state is $P_1 : R_2$ and $P_2 : R_1$. Let's do the lock dance!
>
> (i) P_1 releases R_1 ($P_1 : \emptyset$, $P_2 : R_2$)
>
> (ii) P_2 releases R_2 ($P_1 : \emptyset$, $P_2 : \emptyset$)
>
> (iii) P_2 acquires R_1 ($P_1 : R_2$, $P_2 : \emptyset$)
>
> (iv) P_1 acquires R_2 ($P_1 : R_2$, $P_2 : R_1$)

Conclusion

There is no universal solution to all deadlocks. Determining which solution to use is on a case-by-case basis, and fortunately for us, we only need to implement one of the four!

14.5.6 A Deadlock "Solution"

We can also elect to simply ignore the problem. In many cases, deadlocks are *very* improbable and implementing any of the solutions provided above can be very expensive. So, we can just forget about them and pray to the CS gods that we don't run into a deadlock.

Deadlock Detection and Recovery

We can allow deadlocks to occur, but we want to be able to detect them once they occur (the sooner the better). Once we detect them, we need a method of breaking them to continue execution. Whether or not this is a good idea depends.

In general, it's probably a more practical approach since the overhead and complexity of deadlock-proofing your system may be too expensive. However, in critical systems where resource availability is crucial (e.g. real time systems), we might want to invest the time and energy into preventing deadlocks, since they can lead to severe disruptions, data loss, or even safety hazards.

Implementing Detection

We can implement deadlock detection by using a wait-for graph or an equivalent data structure. When a lock request is made, the system updates the wait-for graph and checks for the presence of a deadlock (cycle detection).

Whether or not it's better to reject a lock request (that will lead to deadlock) and not let the requester block depends. If we reject a lock request, there's no deadlock, but it might result in process disruptions and inefficiencies. If we allow the requester to block, we may get deadlock, but the system will be more resource-efficient overall.

Implementing detection may be challenging however, since we need to identify *all* resources that can be locked.

---

[23]DAG: Directed Acyclic Graph

Application Level Deadlocking

Some applications include their own internal locking mechanisms independent of the operating system. Since the OS doesn't know about these locks, it cannot offer any help. Here, deadlock detection may be appropriate since the application itself has the necessary information to identify and handle deadlocks.

14.6   Health Monitoring

Not everything is a deadlock! There are a lot of reasons systems hang and make no progress. Occasionally, it really is a deadlock. Other times, it's something else (e.g. live-lock, lock flaws, etc.). If there are no locks, it's definitely not deadlock. Even if there are, it may not necessarily be deadlock.

We can use service/application *health monitoring* in lieu of deadlock detection. Here, we monitor application progress and submit test transactions. If responses take *too long*[24]. Health monitoring is much easier to implement than deadlock detection and can detect a wider range of problems, including (but not limited to):

 (i) Live-lock: A process is running but unable to proceed due to unmet dependencies.

 (ii) "Sleeping Beauty": A process waits indefinitely for an event(s) that will never happen.

 (iii) Priority inversions: Health monitoring can detect when priority inversions cause system hangups!

14.6.1   Monitoring Process Health

We can use a variety of metrics to determine process health. We will cover:

 (i) Obvious Failures

 (ii) Passive Observation

 (iii) External Monitoring

 (iv) Internal Instrumentation

Obvious Failures

We can actively check for obvious failures like abnormal process exits or core dumps. These indications can be monitored and analyzed to identify the cause of failure.

Passive Observation

We can identify processes that are unresponsive or hanging by monitoring CPU usage, blocking status, and network/disk I/O. If a process is not consuming CPU time or blocked for extended periods of time, it may be stuck. Likewise, if a process is not performing expected I/O operations or engaging in network activities, it may potentially be stuck.

External Monitoring

We can interact with processes to asses their responsiveness. Common techniques are pings, null requests, and standard test requests. We can ping the process to measure response time. If the process fails to respond within a given time frame, it may be unresponsive. Like pings, we can send a null/dummy request expecting acknowledgment by the process. Lack of acknowledgment can indicate unresponsiveness. More specifically, standardized test requests expect specific responses from the process. Failure to provide the expected response may trigger alerts.

---

[24]Too long is subjective and is dependent on the system requirements.

Internal Instrumentation

We can embed monitoring and testing directly within the codebase of the process via white box audits, exercisers, and continuous monitoring. White box audits involve reviewing internal code and data structures to identify potential vulnerabilities, inefficiencies, or errors. Exercisers are designed to simulate various scenarios to stress-test the process, which can help uncover unexpected behavior and/or vulnerabilities, particularly in complex systems. Continuous monitoring keeps track of key performance metrics and states within the process. Monitoring tools collect data and trigger alerts when the numbers deviate from the expected behavior.

14.6.2   Unhealthy Processes

When processes are unhealthy, killing and restarting any and all affected software is a common and easy recovery strategy. However, deciding which processes to kill and restart requires a balance between addressing the issue and minimizing disruptions.

It is important to note that unresponsive processes may not necessarily be the cause of the problem. Thus, we need to take into consideration how kills and restarts can impact current clients which are dependent on service API's and protocols. Applications must be designed to handle different types of restarts: cold, warm, or partial. In highly available systems, restart groups are well-defined and specify the groups of processes to be restarted together as well as inter-group dependencies.

14.6.3   Failure Recovery

> **Definition: Cold Restart**
>
> A **cold restart** involves terminating the entire process and restarting it from scratch[a]
>
> ---
> [a]This ensures a clean slate but may incur longer downtime.

> **Definition: Warm Restart**
>
> A **warm restart** involves restarting the process but maintaining existing connections/sessions[a]
>
> ---
> [a]This minimizes disruption but may not solve the problem.

> **Definition: Partial Restart**
>
> A **partial restart** involves restarting only specific components of the process[a].

The failure recovery methodology involves retries, rollbacks, and continued functionality. First, we retry a request (if possible), but set limits on how many/how long we wait. If a request ultimately fails, we want to roll back failed operations to before the request and return an error. Finally, we continue with reduced capacity/functionality, accepting only requests we can handle, rejecting otherwise. Additionally, we implement automatic restarts (cold, warm, partial) and use escalation mechanisms to address failed recovery attempts.

Interlude: Making Synchronization Easier

Locks, semaphores, and mutexes are hard to use correctly, since they may not be used when they're needed, may be used incorrectly, and may lead to deadlock or other hanging situations.

One way we can make synchronization easier is to automate the generation of serialization mechanisms. Here, shared resources (objects with methods that require serialization) are identified. Code is written to operate on shared resources without *explicitly* adding synchronization. The compiler then generates the required locking and releasing mechanisms to ensure proper serialization.

14.7   Monitors

> **Definition: Monitors**
>
> **Monitors** are objects with built-in synchronization mechanisms.

We introduce the concept of monitors as protected classes. Here, each monitor object is associated with a mutex that is automatically acquired when a method is invoked on the monitor and released upon method return. Monitors provide encapsulation, allowing developers to manually avoid identifying critical sections, and clients are relieved of the responsibility of managing locks.

14.7.1   Simplicity v. Performance

Monitors provide simplicity in synchronization by automatically locking the *entire* object during method invocations. Since objects are locked for the entire duration of any method invocation, it is a conservative approach to synchronization and can potentially lead to performance issues. Locking the entire object can eliminate parallelism and create the potential for thread contention, resulting in convoys (See **14.3.4 The Convoy Effect**). When implementing synchronization primitives, we consider the trade-offs of simplicity v. performance. Fine-grained locking is difficult and error prone, but often performs well while coarse-grained locking may be simpler to implement, but can create bottlenecks.

14.7.2   Java's Synchronized Methods

In Java synchronized methods, each object has an associated mutex and is acquired for specified synchronized methods. Here, not *all* methods need to be synchronized; synchronization is needed only for the methods with access to shared resources. The mutex is automatically released upon the *final* return of the synchronized method.

Here, nested calls by the same thread do not reacquire the mutex, avoiding unnecessary locking and unlocking. Static synchronized methods lock the class-level mutex, affecting all instances of the class. Advantages include finer lock granularity and a reduced risk of deadlocks, but the cost usually involves the responsibility of developers to *correctly* identify which methods need synchronization.

Part III

Persistence

Chapter 15

Devices and Device Drivers

15.1 Overview

This chapter covers the OS's role in properly handling devices via device drivers.

> **Definition: Peripheral Device**
>
> A **peripheral device** is an external device that is attached to the computer to perform specific functions.

Each peripheral device has code associated with it for performing operations and integration into the system. In modern commodity operating systems, the amount of code dedicated to handling devices is substantial and can outweigh other parts of the system's codebase!

Peripherals are usually connected to the computer via a bus, which facilitates communication between peripherals and other system components. They are designed to perform specific (usually predefined) functions rather than independently executing arbitrary computations. The system sends a signal on the bus to instruct the peripheral to perform its designated task, which is then performed asynchronously alongside other system activities. Once finished, the signal is sent back from the peripheral to the system on the bus to communicate the results of the operation.

15.2 Devices and Performance

Compared to the CPU, bus, and RAM, most peripheral devices are *slow*[1]. Consequently, managing devices *efficiently* presents performance challenges. The system operates at the speed of the CPU, bus, and RAM, but correct behavior often requires interactions with *slow*[1] devices. Thus, it is up to the system to effectively manage the discrepancy in speed to ensure accurate functionality and optimal performance!

15.2.1 Why the Operating System?

Peripheral devices are often managed by the operating system rather than user-level code for various reasons.

Criticality for Correctness

Certain devices are integral to the proper functioning and correctness of the entire system.

> **Example: Flash Drives**
>
> A flash drive that holds swap space is crucial for efficient memory management, an OS service (See **9 Memory Management**)! Managing such critical resources requires coordination and control at the OS level to ensure reliable operation.

---

[1]Sometimes several orders of magnitude slower than the CPU, bus, or RAM.

Shared Access

Many devices must be shared among multiple processes which requires OS-level control! Managing shared access in a fair and efficient manner requires sophisticated synchronization mechanisms and resource allocation strategies.

Complexity

Handling shared resources involves intricate resource management (including locking, queuing, and prioritization). Such complexity is beyond the capabilities of user-level code and requires OS-level control.

Security

Certain devices have security implications, and as such we need a trusted system to manage them. Oh look, the OS is^2 be trusted!

> **Example: Network Interfaces**
>
> Network interfaces that handle communication between applications and external systems require OS-level control to ensure a secure channel for communication.

15.3 Device Drivers

> **Definition: Device Driver**
>
> A **device driver** is specialized software that acts as a bridge between a computer's OS and specific hardware (peripheral) devices, enabling communication and interaction between software and hardware components.

Device drivers enable us to interface with the device from the application layer! When we need to interact with the device, we send a signal to the OS which will in turn call the appropriate device driver. The device driver then feeds detailed instructions to the hardware, performing the desired task.

Code for hardware devices is usually specialized to their unique functionalities. The code serves as a *driving* force behind the device, enabling it to carry out its intended operations. Thus, each hardware device within a system usually has its own driver (code segment).

15.3.1 Properties

Let's take a look at typical properties of device drivers. They are:

   (i) Device drivers are highly specific to the particular hardware device(s) they are meant to support.

  (ii) Device drivers are inherently modular, allowing them to be developed and maintained independently.

 (iii) Device drivers typically interact with the rest of the system via limited and well-defined (see *(i)*) interfaces, promoting compatibility and predictable behavior.

 (iv) Correctness is paramount to a device drivers' utility since it affects both the accuracy of the operation it implements as well as the system as a whole.

  (v) Device drivers are often developed by programmers with an in-depth understanding of the *specific*[3] device's functionality.

---

[2]should*

[3]Note that these developers may not be experts in the broader system, but they need not worry about that (see *(ii)*).

15.3.2 Abstractions

Let's abstract away device drivers!

> **Abstraction: Driver Abstractions**
>
> We define an idealized class of devices, an *abstraction* over device drivers. These classes define expected behavior/interfaces that the drivers will support.

These abstractions over device drivers provide a structured way to interact with a diverse set of hardware devices. Mainly, it lets device drivers to adhere to a common framework by abstracting device-specific complexities. Further, they regularize and simplify the interaction between software (applications) and hardware (devices).

As with any abstraction, driver abstractions encapsulate the knowledge of how to use devices effectively, translating standard operations we interface with into device-specific actions. Consequently, they provide a consistent and intuitive interface for users and ensure proper coordination between devices and software. Furthermore, we have fault handling embedded in abstractions, guiding the handling of recoverable device-level faults and avoiding their escalation into system-wide faults.

15.3.3 Generalizing Abstractions

At first glance, it may seem that each device deserves its own unique driver. But upon closer inspection, we can see that there are many commonalities between them, particularly among classes of devices.

> **Example: Class of Devices**
>
> Let's look at the class of flash drives. Here, we see that *all* flash drives utilize NAND flash memory to store data. We can leverage commonalities such as the NAND flash memory to build an abstraction layer atop the *class* of flash drives.

15.3.4 Providing Abstractions

The OS will define device *classes* (e.g. flash, display, printer, etc.). These classes define the expected interfaces/behavior; i.e. *all* drivers in the class supports *all* the standard methods defined by the OS.

15.4 Interfaces

15.4.1 Device Driver Interface

> **Definition: Device Driver Interface**
>
> The **device driver interface (DDI)** is a standardized set of top-end entry points that connect the operating system with device drivers.

The DDI serves as a basis for device-independent applications and enable the system to seamlessly integrate new devices. It plays a critical role in providing a contract for third-party developers and is composed of entry points that align with syscalls (like `open()`, `close()`, `read()`, `write()`) and OS frameworks (like block I/O for flash drivers or network protocols for network drivers).

15.4.2 Driver/Kernel Interface

> **Definition: Device/Kernel Interface**
>
> The **device/kernel interface (DKI)** is the specification of bottom-end services provided by the operating system to device drivers.

The DKI outlines the functionalities that drivers can request the kernel to perform, similar to an ABI (See **4.2 Application Binary Interface**). It is essential for the DKI to be well-defined and stable to facilitate teh development of third-party drivers and to ensure backwards compatibility. Each OS has its own DKI, but they are all similar.

> **Example: "You'll Never Find Someone Like Me"**
>
> All DKI's provide functionalities like memory allocation, data transfer and buffering, I/O resource (ports, interrupts, etc.) management, DMA, synchronization, error reporting, dynamic module support, configuration, plumbing, and more!

> **Example: Linux Device Driver Abstractions**
>
> Linux takes inspiration from older Unix systems and organizes devices into several super-classes (e.g. block, character, (potentially) network devices). Each super-class defines a set of common behaviors and interfaces for device drivers. This classification allows Linux to provide a structured framework for various types of device drivers and enhances code reusability.
>
> Classes provide a good organization for abstraction since they provide a common framework to reduce the amount of code required for each new device. However, it is important to note that a *lot* of driver functionality is specific to the device, implying that class abstractions don't cover *everything*, but are rather used to ensure all devices in a class provide certain minimal functionalities.

15.5   Device Drivers in Operating Systems

There are usually a lot^4 of device drivers in a system, most of which are relatively independent. So, a pluggable model is commonly used to integrate device drivers into the OS, especially since we may need to add more device drivers in the future. The operating system provides mechanisms that enable users to plug in specific drivers in well-defined ways, simplifying the process of modifying, updating, and/or expanding driver support in the OS.

15.5.1   Layering Device Drivers

Device drivers have multiple layers reflecting different levels of interactions and functionality. At the lowest layer we have interactions with the bus. Here, we have standardized processes for addressing devices, signaling coordination, and data transfers. Interactions at this level are relatively independent of the specific devices that are in use. At the highest layer, we have relatively standardized interactions, often involving file-oriented approaches for communication. Between these two layers, we have device-specific interactions which accommodate the unique behaviors and features of individual devices. These layers allow for a modular development, encapsulation of device-specific complexities, and separation of concerns!

15.5.2   Device Driver Code Operating Systems

While device driver code *can* be integrated into the operating system, we often distribute code based on the functionality it brings. Common functionalities like caching, file systems code (independent of a particular device), and network protocols (above physical/link layers) are best suited to be part of the operating systems. Conversely, specialized functionalities that differ between devices are better suited for device drivers.

---

[4]A Linux 2.6 kernel came with over 3200 drivers!

15.6   Devices and...

15.6.1   Interrupts

Devices in operating systems rely heavily on the interrupt-driven model for communication and coordination. It is important to note that drivers are not treated as processes and therefore not scheduled. Since they work at a (much) slower speed than the CPU, drivers typically perform their tasks independently while the CPU engages in other activities. Interrupts are then used to alert the CPU and gain its attention when they require processing.

15.6.2   Buses

Devices are not directly connected to the CPU. Instead, both the CPU and devices are connected to a bus (which can be the same or differ between the two). Devices communicate with the CPU via the bus for both sending and receiving interrupts as well as for transferring data and commands.

Devices signal the controller when they are done/ready. When the device finishes, the controller puts an interrupt on the bus, which then transfers it to the CPU.

Aside: CPU's and Interrupts

Note that interrupts are similar to traps! Traps come *from* the CPU, whereas interrupts are caused externally *to* the CPU. Unlike traps, interrupts can be en/disabled by special CPU instructions. That is, devices can be told when they may generate interrupts. Furthermore, interrupts may be held *pending*[a] until the software is ready for it.

---

[a]Pending state: The interrupt is recognized by the system but is not immediately serviced by the CPU.

15.7   Device Performance

This section explores how we can efficiently utilize the devices in our system.

15.7.1   Good Device Utilization

Recall that key devices, such as those handling file I/O and network communication, are notably slower than the CPU. When these devices are underutilized and remain idle, their throughput drops, which in turn can lead to lower overall system throughput, longer service queues, and slower response times. The consequences of such inefficiencies are reflected in degraded system performance and a less responsive user experience.

It is critical to strike a balance between high level of activity for these key devices and reducing CPU wait time. A common strategy is to start request $n + 1$ immediately after request n finishes.

Example: Device Delays

Suppose we have a real time system that interfaces with several devices. Delays in device utilization can disrupt real-time data flows, resulting in unacceptable performance numbers and potential data loss!

How do we achieve good device utilization? Parallelism! Since devices operate independently of the CPU, they can operate in parallel with the CPU. However, one key challenge is how to address a situation where both the device(s) and CPU need to access shared memory (RAM). It is essential to manage and coordinate access to RAM to prevent conflicts, ensure data consistency, and optimize system performance.

Aside: CPU Caching

Modern CPU's try to avoid going into RAM by utilizing registers and on-chip caches to store and retrieve frequently used data and instructions quickly. By minimizing the number of trips to RAM (sometimes referred to as a cache hit), the CPU can operate at much faster speeds and achieve better performance.

CPU caching frees up the memory bus for devices to use, offloading some of the bus-related activities from the CPU and potentially improving system performance. We need to balance memory bus usage between devices and the CPU to avoid contention and ensure optimal parallelism.

15.7.2 Direct Memory Access

Definition: Direct Memory Access

Direct Memory Access (DMA) allows two *devices*[a] to transfer data directly between each other without involving the CPU as an intermediary.

------

[a]These devices must be attached to the memory bus.

While DMA offers efficient data transfer, it also limits the memory bus; the memory bus can only be used for one purpose at a time, so if DMA is active, it's not servicing the CPU. Fortunately, the CPU usually doesn't require bus access during DMA operations. DMA enables data to e moved from a device to memory at the speed of the bus/device/memory, bypassing the CPU.

15.7.3 Keeping Devices Busy

Recall that we want to keep key devices busy and optimize their utilization within the OS (See **15.7.1 Good Device Utilization**). We can do this by utilizing several techniques.

 (i) We can allow multiple pending requests at the same time by queuing them, similar to how we put processes in a ready queue.

 (ii) We can utilize DMA for data transfers to minimize delays and overhead on the CPU.

 (iii) We can coordinate the process of handling completed requests via interrupt-driven mechanisms (See **15.6.1 Interrupts** and **15.7.1 Good Device Utilization**).

15.7.4 Transfer Size

Bigger data transfers are non-trivially more efficient than smaller transfers. This is because data transfers come with inherent overhead per operation, including factors like DMA, device-specific tasks, and OS involvement. Overhead activities involve setting up the transfer, initiating new operations, and handling completion interrupts. Thus, larger data transfers are more efficient since they have lower overhead per byte! These efficiency gains are not limited to software and extend to hardware and other contexts as well! The principle of reduced overhead per byte is a fundamental aspect of optimizing data movements and resource utilization.

15.8   I/O and Buffering

> **Definition: Buffer**
>
> A **buffer** is a temporary storage area used to hold data that is ready to be processed or transferred.

Recall that I/O requests involve transferring data between memory and devices. Data that is part of I/O operations is stored in memory locations called buffers. Buffers play a key role in facilitating efficient data movement and communication between devices and memory (especially in I/O). They usually contain data that is ready to be sent to a device or is awaiting data from a device.

An essential aspect of buffer management is ensuring that buffers are available when devices are prepared to use them. The OS is responsible for coordinating the availability of buffers to ensure smooth data transfers.

15.8.1   Buffering Issues

While fewer and larger data transfers are more efficient for I/O operations, they may not necessarily align with application requirements since natural record sizes are often small. The operating system can address this issue by employing various buffering strategies.

We can consolidate I/O requests to optimize data transfers by maintaining a cache of recently used disk blocks, enhancing the efficiency of subsequent operations. For small write operations, the OS accumulates the data and flushes it out as blocks fill up, minimizing the overhead associated with frequent writes.

When reading data, the OS reads entire blocks and delivers the requested data from the cached blocks, enhancing read performance. Further, we can employ read-ahead; the OS anticipates upcoming read operations and proactively reads/caches blocks that have not yet been requested.

15.8.2   Deep Request Queues

Deep request queues refer to when we have a large number of queued I/O operations. Maintaining such a queue helps keep the device(s) busy, minimizing idle time. For example, deeper queues also contribute to reducing mean seek distance and rotational delay in disk-based devices. Furthermore, adjacent requests may be combined in the queue, optimizing data transfers. In some cases, certain write operations can be avoided or optimized via efficient queue management.

We can achieve a deep request queue in a multitude of ways: we can have many entities make requests, individual processes make parallel requests, read-aheads, and write-back cache flushing.

15.8.3   Scatter/Gather I/O

Since user buffers are paged in virtual memory, buffers may be spread all over physical memory! Scatter/gather I/O is when we read from/write to multiple page frames, allowing data to be efficiently transferred between user buffers and devices. There are three basic approaches to address scatter/-gather I/O:

(i) Copy all user data into a physically contiguous buffer.

(ii) Split logical requests into chain-scheduled page requests.

(iii) Utilize teh I/O MMU to automatically handle scatter/gather operations.

15.8.4   Memory Mapped I/O

Memory-mapped I/O is an alternative to DMA, and is used for certain types of devices. While DMA is designed for large contiguous transfers, they may not be the best fit for devices requiring frequent, small, sparse transfers. Memory-mapped I/O treats registers or memory in a device as part of the regular memory space, accessible through memory operations.

Example: Display Adapters

This approach is particularly relevant for devices like bit-mapped display adapters, enabling efficient updates to displays with low overhead and no interrupts. Here, each word of memory corresponds to one pixel on the display. Applications can use ordinary memory stores to update the display, simplifying programming and providing efficient access to device-related memory.

Chapter 16

File Systems

16.1 Overview

Persistent data storage is essential for retaining data across reboots and power downs. Even the operating system relies on persistent storage to maintain its state! There are several options for persistent storage: raw storage blocks, databases, and file systems.

Raw Storage Blocks

Using raw storage blocks involves storing data directly on storage devices like hard disks or flash drives without any *structure*. While this approach is flexible when it comes to data layout, it's not very user-friendly and is hard to manage due to its low-level nature.

Databases

Databases provide a *structured* way to store and manage persistent data. They offer features like data organization, indexing, and querying, making them good for structured data management. However, databases often come with overhead and complexity, especially when the data organization is more straightforward, leading to a bloated system.

File Systems

File systems offer an organized and *user-friendly* approach to structuring persistent data. They provide a hierarchy of directories and files, making it intuitive for users and programmers to store/retrieve data. File systems also manage metadata, permissions, and access control. This option strikes a balance between raw storage blocks and databases, and is what we will be focusing on in this chapter.

> **Definition: File**
>
> A **file** is a self-contained entity that can store various types of data (e.g. documents, spreadsheets, messages, programs, etc.).

The basic idea of a file system is to organize data into coherent units, each of which are referred to as a *file*. The primary goal of a file system is to provide efficient access to files and a powerful organizing principle for managing the collection of files.

16.1.1 File Systems and Hardware

File systems are typically stored on hardware that provides persistent memory (e.g. flash), with the expectation that files stored in a particular location (on flash for example) will remain there between access instances.

For optimal performance, file systems should also be implemented with the underlying hardware in mind for optimal performance while also striving for cross-hardware compatibility.

> **Example: Flash Drives**
>
> The flash drive is a solid state persistent storage device; i.e. it has no moving parts. Reads/writes are fairly *fast*[a], but a given block can only be written once. Writing over a block requires erasing, which is slower and involves erasing larger sectors of the drive.
>
> ---
> [a]Reads up to 100 MB/sec, writes up to 40MB/sec.

16.1.2   Data v. Metadata

> **Definition: Data and Metadata**
>
> **Data** refers to the content that a file is intended to store (e.g. text, images, program instructions, etc.).
>
> -
>
> **Metadata** refers to information about the file (e.g. attributes like file size, creation date, permissions, etc.).

Both data and metadata need to be stored persistently within the file system. Typically, data and metadata are stored on the same storage hardware to ensure that both are accessible together.

> **Aside: Uniform Functionality**
>
> File systems should be designed to function uniformly across various storage media. This enables the same program to interact with the file system regardless of the storage medium being used (e.g. flash v. disk), enhancing program portability and reducing *complexity*[a]. By maintaining a consistent interface, the file system can seamlessly manage different storage media without requiring major changes to program code!
>
> ---
> [a]Complexity of adapting programs to different storage technologies.

16.1.3   Properties

Properties we want in a file system include (but are not limited to):

(i) Persistence: The file system should ensure that data and metadata are stored persistently even between power cycles.

(ii) Easy Use Model: The file system should be user-friendly for both accessing individual files and organizing collections of files.

(iii) Flexibility: The file system should not impose limits on the number of files, file sizes, types, or contents, allowing users to manage diverse data.

(iv) Portability: The file system should be able to function consistently across different hardware device types, ensuring program portability.

(v) Performance: The file system should be robust and dependable, minimizing the risk of data loss/corruption.

(vi) Security: The file system should incorporate appropriate security measures to protect data from unauthorized access or tampering.

Aside: Issues

There are some concerns we should bring to light before continuing the discussion on file systems:

(i) Performance: Ideally, we would like our file system to be as fast as things like the CPU, bus, and memory. However, these devices operate at *nanoseconds* today, and flash drives are roughly 1000x slower. This implies that we need to do some *serious* work to hide the mismatch in performance speeds.

(ii) Reliability: Trivially, persistence implies reliability; we want our files to be there when we check, *no exceptions*. This implies our file system needs to be free of errors on both the hardware *and* software side, the latter of which may be hard to ensure (see **II Concurrency**).

(iii) Security: We want to ensure controlled and well-defined access to data; i.e. data owners should have the ability to determine who has access to their data via an access control model and mechanism. We need *strong* guarantees that the system will enforce owners' desired controls, implying we'll need to check permissions on access. But remember, we need to strike a balance with *(i)*.

File systems are built using multiple layers of abstraction. At the top, applications interface with and access *files*. At the bottom, various block devices are reading/writing to *blocks*.

Abstraction: File Systems

Like with any abstraction, we do this for simplicity and portability. Directly translating from application file operations to devices' block operations are extremely difficult and have a lot of variable parameters. Different devices may have varying block sizes, addressing schemas, and protocols. Furthermore, direct translation may not take advantage of higher-level optimizations like caching and buffering, leading to suboptimal performance. Lastly, we want to make our code *flexible* and *maintainable*. Direct translation goes against both.

16.2 File System API

Ideally, we would provide a single API to programmers and users for *all* files regardless of how the file system is actually implemented[1]. The File System API can be categorized into three groups:

(i) File Container Operations: These operations handle creating/deleting and opening/closing files. These operations manage the overall file structure and relationships between files and their metadata.

(ii) Directory Operations: These operations handle directories and their contents, including creating/deleting, listing, and navigating directories.

(iii) File I/O Operations: These operations handle read/write operations from/to files. These operations manage data transfer between programs and files in the file system.

The API abstracts away the underlying implementation, allowing the user to focus on interfacing with the API without worrying about low-level details.

16.2.1 File Container Operations

These operations involve standard file management system calls that manipulate files as *objects*[2]. These operations are implemented using standard file system methods, which handle tasks such as getting/setting attributes, ownership, protection, creating/destroying files/directories, and managing links. The actual work of performing these operations occurs within the file system implementation.

---

[1]This is a requirement for portable programs!

[2]These operations focus on managing the files themselves rather than the content of them.

(i) Get/Set Attributes: Functions to retrieve/modify attributes associated with files (e.g. permissions, timestamps, ownership).

(ii) Create/Destroy Files/Directories: Functions to create new files/directories or destroy existing ones.

(iii) Create/Destroy Links: Functions to create/destroy hard/symbolic links to files.

16.2.2 Directory Operations

These operations center around translating file names into lower-level file pointers within the file system structure. The main focus of directory operations is to facilitate tasks related to searching for files by name, creating new name-to-file mappings, and listing known names within a directory.

Directories can represent a complex logical hierarchy of files and subdirectories, even if the underlying storage medium doesn't impose a strict hierarchical structure. They also provide users with tools to navigate and manage the organization of files within a file system effectively.

(i) Searching: Function to search for a file in a file system by its name.

(ii) Mappings: Function to create a new name-to-file mapping to enable *(i)*.

(iii) List: Function to list all known files in a given directory.

16.2.3 File I/O Operations

These operations enable applications to interact with the data contained in files within a file system. Operations include opening/closing files, reading/writing from/to files, seeking to different positions in files, and mapping files into the address space of a process (See **6.1 Process Address Space**). We can implement these functions using a combination of logical block management, data copying, and interaction with the file system's buffer management.

(i) Open/Close: Functions to initialize/destroy an instance of a file using its name.

(ii) Read/Write: Functions to read data from and write data to files. These operations involve logical block management and data transfer between user space and file buffers. Data is fetched into logical blocks, and copies are made between user space and file buffers.

(iii) Seek: Function to change the logical offset associated with an open instance of a file, facilitating navigation within the file's data.

(iv) Mapping: Functions to map the file(s) into the address space of a process. File block buffers are represented as pages of physical memory. By mapping the file, data can by directly accessed from memory, and page swapping is managed by the OS (See **9.10 Paging**).

16.3 Virtual File System Layer

The Virtual File System (VFS) layer acts as a *federation layer* (See **5.4 Generalizing Abstractions: Introduction to Federation Frameworks**) that generalizes different file systems, allowing the operating system to treat all file systems in a uniform manner. This layer enables a plug-in interface for various file system implementations. Different file systems (e.g. DOS FAT, Unix, EXT3, etc.) are implemented as plug-in modules with the same basic methods for file management (See **16.2 File System API**).

Higher level clients interact with the VFS layer through the standardized methods/properties without needing to know the specific implementation details of individual file systems.

16.3.1   The File System Layer

The file system layer is where the code implementation for each file system is stored. All file systems are built atop block I/O, which allows them to be independent of the underlying physical devices. This layer provides a common interface and functionality for different file system types. All file systems perform a set of core functionalities (See **16.2 File System API**).

> **Aside: Why Multiple File Systems?**
>
> Certain storage devices work better with certain file systems! Not only that, they provide different types of services. It is to remember that this is CS, and tradeoffs are inevitable.
>
> > **Example: New File System New Services**
> >
> > Suppose we have two file systems on our computer, F_1 and F_2. Despite having the same interface, F_1 may be more reliable but slower than F_2 and vice versa. This simple example illustrates the advantages of supporting multiple file systems on a single computer.

16.4   File Systems and Block I/O

File systems typically sit on an abstracted block I/O layer; i.e. all block devices implement standard operations (e.g. read/write, map block numbers to device addresses, etc.). One of the main functions of the general block I/O layer is to map logical block numbers (used by the file system) to their corresponding device addresses (located on the storage device), allowing direct communication between the file system and storage device. This layer also encapsulates the specific details of device support, including (but not limited to) completing I/O operations, error handling, and handling size alignment limitations.

16.4.1   Device Independence

We use a device independent block I/O abstraction because it is more powerful over using generic drives. It allows for the implementation of a unified LRU (See **10.1.4 Least Recently Used and Clock Algorithm**) buffer cache which can hold both frequently used data and prefetched read-ahead data, optimizing access patterns and reducing I/O latency.

   The device independent layer also provides buffers that facilitate data re-blocking; adapting the file system block size to match the device block size or user-requested sizes. Along with this comes automatic buffer management, which handles the de/allocation of buffers and ensures that modified buffers are automatically written back to the storage device.

16.4.2   Cache

There are many advantages for implementing a buffer cache. Mainly, file access patterns are characterized by high reference locality at multiple levels, leading to repeated access to data and metadata.

   Users often perform small read/write operations on parts of a single block, reusing that block in subsequent operations. Moreover, the OS regularly consults the same metadata blocks for various tasks. The cache optimizes file access by limiting the number of times we need to access the disk, improving performance and reducing latency.

> **Corollary: Single Cache**
>
> If caches are so good, why not have one per process (or user? or device?)? Well, a single cache is more efficient when multiple users access the same file. More importantly, a single cache provides a better hit ratio compared to multiple independent caches (regardless of how they are spread out).

16.5　File System Control Structures

Recall that a file is a named collection of data (e.g. text file, C program, etc.). The primary roles of a file system is to store/retrieve data as well as manage the media/space where data is stored.

16.5.1　Finding Data on Devices

One of the primary operations we need to implement is finding data on devices; i.e. managing the space on devices. Space management is very complex, as there are a lot of variable parameters.

> **Example: Harder Tetris**
>
> Space management on devices can get very complex since there are millions of blocks and thousands of files on the system. Furthermore, these files are continuously created and destroyed, and we have to manage that as well. What happens when we want to extend the file after they have been written? We need to deal with that as well.
>
> Even if we manage the above, we still need to consider how our data placement will effect performance. Evidently, poor space management leads to poor performance.

To start, we have a data structure (on-device) that stores information for each file on the file system.

File Control Structures

On-device file control structures provide descriptions of important attributes[3] of a file on the storage device itself. Virtually all file systems incorporate such data structures, each with their own implementation, performance characteristics, and capabilities[4]. On-device structures are usually paired with an in-memory representation of the same information, which helps facilitate efficient file system operations (reduced disk access).

Problems to Solve

Recall a file typically consists of multiple data blocks. As such, the control structure needs to be able to find *any* of them quickly; i.e. we shouldn't need to scan the entire file to find a particular block.

Moreover, blocks can and will be changed, and new/existing data can be added/deleted from/to the file. The control structure we implement should address these issues as well.

We also have to address sparse files; (potentially large) files that have not been "filled in" in its entirety upon creation. Adding data into these blocks may not necessary be linear. That is, we may need to write into the middle of a file rather than appending it to the end.

16.5.2　In-Memory Representation

When a file is opened, we create the in-memory structure for that file (See **16.5.1 File Control Structures**). It is not an *exact* copy of the on-device version, since that version points to device blocks, whereas the in-memory version points to RAM pages (or indicates that a given block isn't in memory). The in-memory version also tracks which blocks have been written.

Multiple Opens

In-memory control structures are per-process; i.e. if multiple processes have the same file open, they each have an independent structure. The reason for this is because in-memory structures typically contain a cursor pointer indicating how far into the file data has been read/written. Most likely, different processes are going to have different cursor pointer values.

But what if cooperating processes are working with the same file? They may want to share a file cursor and therefore the same in-memory structure! Moreover, how can we know when all processes are done with an open file (for memory reclamation)? We have a two-level solution for this! We will

---

[3]Including where the file is located!

[4]Another example of how the choice of implementation can impact what a file system can do.

have one in-memory structure shared by *everyone* that has a particular file open. We will then have a secondary in-memory structure that is specific to each process that has the file open.

Chapter 17

File Systems: Structure

17.1 Overview

Most file systems live on block-oriented devices like SSD's or HDD's. Volumes on these devices are partitioned into fixed blocks of varying sizes (e.g. 512, 1024, 2048, 4096, 8192 bytes). Most of the blocks are used for storing user data (in the form of files). Some blocks are used for storing and organizing metadata (e.g. description of the file system, file control blocks, list of free blocks, etc.). All file systems have these data structures, but implementations can vary depending on the goals and objectives of each system.

17.1.1 The Boot Block

> **Definition: Boot Block**
>
> The **boot block** contains the code that allows the machine to boot the OS!

The 0th block of a device is usually reserved for the boot block. File systems typically don't have control over the boot block and simply ignore it. So, file systems typically start on block 1.

17.1.2 Managing Allocated Space

Deciding how to allocate space is a core activity for a file system. We can:

 (i) Allocate fixed-sizes, but that causes internal fragmentation (See **9.1.1 Problems**).

 (ii) Allocate fitted-sizes, but that causes external fragmentation (See **9.2.1 Problems**).

(iii) Allocate space in pages, but we need to know how many chunks ("pages") a file can hold. This is often determined by the file control structure, as it defined the maximum number of pages a file can have before it's considered "full".

17.2 Linked Extents

Simply, we can create a linked list structure; the file control block contains exactly one pointer (the first chunk of the file), and each chunk contains a pointer to the next. While this allows us to add arbitrarily many chunks to each file, it takes away a small portion of every chunk (for the pointer[1]) and requires a linear scan to read chunk n.

---

[1] Alternatively, pointers can be in auxiliary "chunk linkage" table.

17.3   The DOS File System

In the DOS file system, space is divided into "clusters" (alternative name for chunks). The cluster size is typically a multiple of 512 bytes and is fixed for each file system. Clusters are sequentially numbered from 1 to n, where n is the total number of clusters in the file system. The file control structure points to the first cluster of a file, initiating the file's data allocation.

17.3.1   File Allocation Table

The File Allocation Table (FAT) consists of one entry per fluster, where each entry contains the number of the next cluster in the file. An entry of 0 indicates that the cluster is not allocated to any file, while an entry of -1 indicates the end-of-file (EOF) marker.

17.3.2   Characteristics

To locate a specific block within a file, we follow a chain of pointers through the FAT, starting with the number of the first cluster obtained from the directory entry.

The entire FAT is maintained in memory, eliminating the need for disk I/O when finding a cluster, speeding up the process[2].

Unfortunately, DOS doesn't support sparse files; if a file has a block n, it *must* have all blocks $< n$.

The width of the FAT determines the max file system size. The number of bits used to describe a cluster address in the FAT determines the address space available for clusters. Originally, clusters used 8 bits to describe cluster addresses, but this was eventually expanded to accommodate larger file systems, using up to 32 bits.

> **Example: File Size**
>
> Let's take a look at how big a file we can handle! Originally, we had 4096 entries with each cluster being 512 bytes. So, we have $2^{12} \cdot 2^9 = 2^{21} \approx 4MB$!

17.4   File Index Blocks

An alternative to FAT's, we have File Index Blocks. A file control block points to all blocks within the file. This method offers fast access to *any* desired block within the file. However, we are limited by the maximum number of pointers the file control block can hold.

To address this, we can use extent descriptors that point to larger sections of data than individual blocks. Unfortunately, we still have a limit on the number of pointers as well as possible fragmentation.

17.5   Hierarchically Structured File Index Blocks

To solve the issue of a file' size being limited by the entries in the file index block, we can use a hierarchical approach. Here, the basic file index block directly points to data blocks similar to traditional methods. Some of these blocks point to other blocks to create a hierarchical structure. While we still have a limit on the number of pointers, it is very large, and this approach offers the potential to adapt to a wide range of file sizes.

17.5.1   Why the Complexity?

While this approach may seem unnecessarily complicated, we prefer this approach since we can access a significant portion (40K if we use 4K blocks) of a file before we need to perform additional disk operations. Additionally, this approach is favored since it can efficiently manage files of varying sizes.

---

[2]Larger files will still be relatively time-consuming.

> **Example: File Sizes Round 2**
>
> The on-disk inode contains 13 block pointers. The first 10 point to the first 10 blocks of the file, 11, 12, 13 to a single, double, triple indirect block[a]. Assuming 4K bytes per block and 4 bytes per pointer, we get:
>
> $$10 \cdot 4KB = 40KB$$
> $$1K \cdot 4KB = 4MB$$
> $$1K \cdot 4MB = 4GB$$
> $$1K \cdot 4GB = 4TB$$
>
> Damn that's a lot of bytes.
> _____
> [a]The indirect block points to 1024 blocks.

17.5.2   Performance

Inodes are cached when files are open, allowing direct access to the first 10 blocks. The remaining blocks require indirect blocks. These indirect blocks support sequential file processing, and block I/O and buffer caching help maintain data blocks in the buffer cache.

Despite needing additional I/O for indirect blocks, the impact is limited to 1-3 extra I/O operations per thousand blocks, with most data blocks being accessible in < 3 reads.

We can also support sparse files via index blocks, similar to how we use page tables for sparse address spaces.

Chapter 18

File Systems: Allocation and Performance

File systems are generally dynamic: we create new files and modify/destroy existing ones. Such changes convert unused disk blocks to used ones (or vice versa). So, we need to be able to efficiently (and correctly) implement these operations.

18.1 Free Lists

We can manage free space in storage devices using free lists (See **9.2.2 Managing Variable-Sized Partitions**). In storage devices, free elements are usually fixed-sized blocks rather than variable-sized partitions. However, challenges in organizing free lists arise: in HDD's, locality matters, and for flash, there are erasure and load leveling challenges.

18.2 File Operations

18.2.1 Creating a File

In Unix, we allocate a free inode by searching the super-block free inode list and taking the first free inode. The super-block is a data structure that contains information about the file system, including the number of free inodes. Once a free inode is found, we mark it as allocated and initialize it with the appropriate metadata (e.g. file type, permissions, ownership, timestamps, etc.). We then give the new file a name.

In DOS, we start by searching the parent directory for an unused directory entry. We then initialize the FCB[1] with the appropriate metadata and give the new file a name.

18.2.2 Extending a File

When an application wants to write more data to a file, it requests that the file be extended to accommodate the new data, which can either be explicitly requested by the application or implicitly requested when we write to a currently non-existent data block.

We then find a free chunk of space large enough to hold the new data, which is often done by traversing a free list (or bitmap). Once found, the file system allocates and reserves the space for the file's extension, ensuring that the allocated space won't be used for other purposes until the file extension is complete. The file's metadata is then updated to associate the newly allocated space with the appropriate address within the file. We can now write to the extended portion of the file.

---

[1]FCB: File Control Block.

18.2.3 Deleting a File

When a file is deleted, we need to release all the space that is allocated to that file. In Unix, we return each block to the super-block free inode list by zeroing the inode and returning it to the free list.

In DOS, we use garbage collection to eventually reclaim the space by identifying and marking deallocated blocks. When a file is deleted, we zero the first byte of the name in the parent directory to indicate that it is available for garbage collection.

18.3 Free Space Maintenance

The file system manager is responsible for managing free space within the file system. Fast de/allocation of blocks are crucial operations that need to be optimized, as they are frequent and impact overall file system performance.

Unlike memory management, choosing which blocks to de/allocate matter due to specific considerations related to storage devices.

> **Example: Different Drives Different Problems**
>
> When using flash storage, we need to keep in mind that we cannot overwrite fully-written blocks. Moreover, it would be beneficial to perform *wear-leveling*[a].
>
> In Hard Drives, it would be beneficial to keep data contiguous for faster lookups!
>
> ---
> [a]Wear-leveling: Distributing write/erase cycles evenly across memory cells to extend the overall lifespan.

Free list organization needs to address both the speed of de/allocation as well as the ability to allocate blocks in preferred locations on the storage device.

18.4 Allocation/Transfer Size

Each I/O operation comes with overhead, including DMA, handling interrupts, and any device-specific costs. As such, minimizing these overheads will improve overall I/O performance.

One way to minimize overhead and increase throughput is to use larger transfer units (or I/O block sizes) to amortize the fixed per-operation costs over a greater number of bytes per operation.

While multi-megabyte transfers are efficient (especially with larger files or streaming data), the optimal transfer unit size can vary depending on the use case, storage technology (e.g. HDD v. SSD), and the characteristics of the workload.

18.4.1 Choosing the Allocation Unit Size

As mentioned above, choosing the allocation size depends on multiple factors, but here are some things to consider:

(i) Small chunks lead to efficient space utilization by minimizing internal fragmentation, but incur more overhead than larger chunks.

(ii) Larger, fixed-sized chunks can lead to internal fragmentation, which can be problematic if the workload involves a healthy mix of small and large files.

(iii) Variable sized chunks can reduce internal fragmentation, but introduces the risk of external fragmentation, making it challenging to allocate larger files contiguously.

18.4.2 Flash Drives

Flash drives put HDD's in their place (the trash can), and their unique characteristics introduce both opportunities and challenges for file system design. Let's take a look at some flash drive characteristics:

(i) Flash is faster than HDD's but still slower than direct access to RAM.

(ii) Unlike HDD's, flash has uniform access speed; i.e. every location on the flash is equally fast to access.

(iii) Flash has limited write endurance for each block. So, file systems often implement wear-leveling to address this issue.

(iv) Flash has the unique trait of being write-once/read-many (WORM) to address *(iii)*. Moreover, flash memory must be erased in large blocks (erase blocks); i.e. we cannot erase smaller portions of flash memory.

18.5 Caching

We can implement read/write caching to reduce the number of trips we need to take to storage.

18.5.1 Read Caching

Read caching addresses the issue of slow persistent storage I/O. While deep queues and large transfers enhance efficiency, they don't drastically expedite the process. To tackle this, we can minimize persistent storage I/O.

This is achieved by implementing an in-memory cache that capitalizes on data locality and reuses the same blocks. By prioritizing cached data, the system can preemptively check the cache before initiating I/O operations, thereby optimizing performance.

Note that the cache's effectiveness is based on data locality and the reuse of the same blocks (See **9.10.5 Locality of Reference**).

18.5.2 Read-Ahead

Read-ahead involves proactively requesting data blocks from a storage device before they are actually requested by a process. This technique is employed to reduce process wait times by ensuring that the required data is readily available.

Read-ahead is particularly beneficial when sequential access is expected, and the client either explicitly requests or appears to be reading data sequentially. However, this strategy comes with potential drawbacks, including the possibility of utilizing device access time for unnecessary data retrieval and consuming buffer space with unneeded blocks[2].

18.5.3 Write Caching

Write caching (deferred writing) is a strategy used to optimize the process of writing data to storage devices. In this approach, most device writes are initially directed to a write-back cache, where they are temporarily stored before being eventually flushed out to the actual storage device. This cache aggregates small writes into larger ones, which can be more efficient when applications perform partial block writes.

Write caching eliminates redundant writes by recognizing scenarios where subsequent data changes or deletions make earlier writes unnecessary. Additionally, the strategy involves accumulating batches of writes in the cache to create larger, more efficient disk access queues, enhancing overall disk scheduling efficiency.

18.5.4 Disk Caching

Disk caching encompasses various techniques to enhance storage performance. General block caching involves storing frequently accessed and recently re-read files, providing buffers for read-ahead and deferred writes.

Conversely, special purpose caches cater to specific needs; directory caches expedite directory searches, while inode caches accelerate reuse of the same file. Although special purpose caches are more intricate, they often outperform general caching by precisely aligning cache structures with actual usage patterns, resulting in improved efficiency.

---

[2]If the preemptively fetched data turns out to be unnecessary for upcoming processes, the buffer space occupied by unneeded blocks is effectively wasted.

18.5.5   Pinning File Data in Caches

Pinning file data in caches involves the selective retention of specific data in memory, preventing it from being replaced according to the typical cache replacement strategy (hence, *pinning* it), often resembling the LRU approach (See **10.1.4 Least Recently Used and Clock Algorithm**).

This strategy ensures that certain data remains readily accessible for immediate reuse. For example, contents of current working directories can be pinned to expedite access during ongoing operations.

> **Example: Pinned Down**
>
> One scenario in which file data is pinned involves the inodes of files associated with processes. By pinning the inodes of files, the system ensures that these crucial structures are readily available in memory, avoiding the potential delay of fetching them from storage when they are likely to be used again!

While pinning data provides performance benefits, it's essential to strike a balance. Pinned data consumes memory resources, and excessive pinning could lead to memory exhaustion. Therefore, careful consideration is required to determine which data should be pinned, based on its frequency of use and its impact on overall system performance.

Chapter 19

File Systems: Naming and Reliability

In file systems, naming files requires a method for referencing them. While the operating system prefers using simple numbers as identifiers, these aren't user-friendly or usable by programs. A more effective naming system is needed to address this. Such a system should be user-friendly, facilitate organized management of numerous files, and be easily implementable within file systems.

19.1 Naming

File systems manage files through internal descriptor structures, but for user convenience, meaningful names are assigned to files. The process of mapping these names to internal descriptors involves several tasks.

When users create new files, the system establishes the link between the provided name and a new internal descriptor. Similarly, given a file name, the system must locate the corresponding descriptor for any operations.

Renaming files while preserving their content and structure is a necessary feature. Users rely on names to organize files, emphasizing the need for efficient name-based organizational tools.

19.1.1 Name Space Structure

> **Definition: Name Space**
>
> A **name space** refers to the entire collection of names managed by a naming mechanism. It encompasses all possible names within the system, including those that could potentially be created in the future under the mechanism's rules.

Name spaces can be structured in various ways to manage the organization and retrieval of files. The structure of a name space influences how names are organized and related to each other.

Flat Name Space

In a flat name space, all names coexist on the same level without any inherent hierarchy. This straightforward approach places all files on an equal footing, making them easily accessible without the need to navigate through complex naming structures. However, this simplicity can also lead to potential naming conflicts, as different files may end up with identical names, causing confusion and hindering efficient file management.

Graph-based Name Space

Alternatively, name spaces can follow a graph-based structure. This can take the form of a strict hierarchical tree, where names are organized in a top-down manner, creating a clear parent-child rela-

tionship. Conversely, a general (usually directed) graph structure allows for more complex relationships between names.

Corollary: Issues

The structure of a name space presents several issues that impact how files are managed and accessed within a file system.

In a flat name space structure, each name can be assigned to only one file within the entire file system. In hierarchical name spaces, the restriction is refined to one file per directory sharing a name.

Another aspect is the number of different names a single file can have. This introduces choices, ranging from having a sole *true name* to allowing multiple aliases for a single file. Decisions around the concept of a *true name* and its attributes can influence how files are perceived and managed within the system.

Issues also arise concerning the consequences of deleting a specific name associated with a file. Are other names linked to the same file affected as well, potentially leading to the removal of the file itself?

Furthermore, considering access permissions, it's essential to determine whether all names connected to a file share identical access rights or if different names can have distinct permissions.

19.1.2 Hierarchical Name Space

Hierarchical name spaces represent an organization of files that follows a graphical structure. Here, directories are files that contain references to other files and function as non-leaf nodes in the hierarchical graph. These directories also serve as contextual units for naming.

The directory structure operates on the principle that each process has an associated current directory. File names are interpreted relative to this current directory. The arrangement of nested directories forms a tree, with files' paths described through this hierarchy.

The hierarchy's expansion stems from a root node, and names originating from this root are called "fully qualified". Despite the typical tree structure, it's important to acknowledge that the hierarchy can actually be more complex, forming a directed graph if certain configurations are allowed, such as files having multiple names.

Understanding and managing hierarchical name spaces involve considerations of current directories, relative and absolute paths, as well as the potential for multiple naming contexts. This system design is a cornerstone for efficient file organization and navigation within a computing environment.

19.2 Directories

Directories in file systems are a special type of file that enables the operating system to link file names with their corresponding physical files. A directory contains a collection of directory entries, each of which provides crucial information about a particular file, including its name. This arrangement allows users to interact with and access files using human-readable names rather than internal file descriptors.

19.2.1 Reading

User applications are allowed to read directories, enabling them to gather information about the files contained within a directory. By reading directories, applications can retrieve details about individual files, such as their attributes and sizes.

19.2.2 Writing

Writing to directories is usually restricted to the OS to ensure the integrity of the directory structure, preventing unintended modifications that could disrupt the organization and accessibility of files.

In special cases, users can initiate writes to directories through specific system calls provided by the operating system. These system calls ensure that changes to directories are performed in a controlled and secure manner.

> **Example: Make What?**
>
> System calls `mkdir()` and `rmdir()` allow users to create and remove directories respectively.

Directories act as a bridge between user-friendly file names and the underlying file system's structure. Their role is vital for maintaining file organization and providing a means for applications and users to interact with files effectively.

19.2.3 Traversing

Entries within directories can serve as pointers to child directories, establishing links to lower levels in the hierarchical structure. These connections enable the hierarchical representation of files and directories within the system.

To access a file within a child directory, a specific naming convention is employed. This convention requires the specification of the parent directory name, followed by the child directory name, and finally, the file name. These components are usually concatenated using a delimiter to form a complete path, indicating the file's location within the hierarchy.

An important consideration in directory navigation is moving upwards in the hierarchy. Many file systems incorporate a special entry within directories to reference the parent directory, commonly denoted as "..". It provides an efficient means of moving up the hierarchy, allowing users and applications to traverse the directory tree in a logical and organized manner.

19.2.4 File v. Path Names

In certain systems, files had *true names*, where each file is associated with a unique identifier stored in a record. This singular identifier represents the exclusive name for that file, minimizing naming ambiguity and ensuring precise identification.

> **Example: DOS**
>
> In systems like DOS, a file's description is contained within a directory entry. The name of the file within the specific directory entry serves as its local name. Conversely, the fully qualified name of the file is constructed by concatenating the directory path from the root to the directory entry in question. This hierarchical path serves as a comprehensive identifier for the file's location within the system!

> **Example: Unix**
>
> Unix file systems provide a unique approach to handling file names and associations with inodes. In contrast to systems like DOS, Unix permits multiple file names to reference the same file, enhancing the user experience and organizational capabilities.
>
> File names within Unix are structured by slashes, resulting in paths that lead to specific files. For example, the format `/user_3/dir_a/file_b` indicates the path to a file named `file_b` located within `dir_a`, which in turn is situated in `user_3`.
>
> The contents of a Unix directory entry consist of two key elements: the name of the associated file, which is relative to the directory containing the entry, and a pointer to the inode representing the file's data and attributes.

> **Aside: Path Names as Sole Identifiers**
>
> Suppose we have a system where files lack inherent names. Here, the naming of files is entirely determined by their directory paths. Every file's name would be a composite of its position within the directory hierarchy.
>
> This approach would remove the need for distinct file names and emphasize the importance of the directory structure. Each file's location within the hierarchy would serve as its sole identifier, with the directory path acting as a complete and unique name.

19.3 Links (in Unix)

Links in Unix don't store the actual file data but represent file names. All substantial file information, such as attributes, permissions, and ownership, resides within the file's inode. Recall that the inode acts as a central repository for metadata, with each file having a single inode regardless of the number of links associated with it.

Access to files through links is *uniform*[1]. If a user has read access to a file, they can create additional links to that file.

However, it's important to recognize that directories are also files, and they have their own set of access control mechanisms. Not all users necessarily possess read or search access to every directory, thus governing their ability to navigate the file system.

The concept of equal access via links underscores Unix's principle of treating all links to a file as equal entities. There is no special significance attached to the first link created for a file or to the link owned by the file's creator. This design choice reflects Unix's philosophy of simplicity and consistency in its file system organization.

19.3.1 Removing Links

When a link to a file is removed, we need to ensure that the other links still point to the file. More importantly, if a file is deleted entirely, we need to ensure that the remaining links are cleaned up and don't reference a non-existent entity.

To resolve this, Unix takes the stance that a file's existence is tied to the presence of at least one active link. This implies that a file will continue to exist as long as there's at least one link that points to it.

To facilitate this approach, Unix maintains a reference count associated with each file's inode. This reference count keeps track of how many links are currently pointing to the file. As long as this reference count is greater than zero, the file remains accessible.

Crucially, the reference count is stored within the file's inode, not within any specific directory. This ensures that the reference count information is maintained consistently across all directories and links associated with the file.

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[1] All links provide equivalent access to the same file data.

19.3.2 Hard Links

> **Definition: Hard Link**
>
> A **hard link** is a reference to a file that points to the file name and its corresponding inode.

Hard links will directly point to the data blocks of the original file. Creating a hard link creates a new directory entry that share the same data on disk. It is important to note that we cannot hard link directories or files on different file systems.

19.3.3 Symbolic Links

> **Definition: Symbolic Link**
>
> A **symbolic link** is a special type of file that holds the path name to another file, indirectly referencing it.

Note that symbolic links are distinct files with their own inodes. When a symbolic link is accessed, the file system automatically opens the file it references. If the referenced file is inaccessible or non-existent, the attempt to access the symbolic link fails.

Unlike hard links, symbolic links do not directly reference inodes. They do not prevent the deletion of the linked file, nor do they influence the link count of the referenced file. Additionally, symbolic links do not guarantee the ability to follow the specified path indefinitely, as changes in the file system's structure can impact their validity.

> **Example: Kinda Like URL's!**
>
> Symbolic links share a conceptual similarity with internet URL's. Just as symbolic links serve as indirect references to files, URL's act as indirect references to web resources. Both symbolic links and URL's offer an abstraction layer that allows users and applications to access resources through a more human-readable or manageable name.

19.4 Reliability

Maintaining the reliability and integrity of a file system is a critical concern, as various factors can lead to issues that compromise data and overall system stability.

System crashes are one of the factors that can disrupt a file system's correct state. A sudden shutdown or failure during file operations can leave the file system in an inconsistent or partially updated state.

Moreover, data loss can arise due to hardware failures, such as disk crashes, or software errors that result in the loss of file data.

In the event of data loss, files can become inaccessible or unreadable. Accidental alterations to file data can further exacerbate the problem, affecting the correctness and usability of the stored information.

Corruption can manifest in various ways, including the loss of free space, references to non-existent files, or the occurrence of over-allocated space due to issues in the free space management. Such corruption can result in file contents being overwritten by unrelated data, which poses a serious threat to data integrity!

Corrupted directories within a file system can have profound implications. They can lead to files becoming unfindable or lost, hampering users' ability to access their data. Moreover, corruption in inodes can result in the loss of file information and pointers, making it difficult or impossible to retrieve files even if their data is intact.

19.4.1 The Core Problem

Unfortunately, file system writes involve more than just writing data blocks to persistent storage. Alongside writing data, various metadata blocks must also be updated to maintain the consistency and integrity of the file system.

> **Example: Meta Metadata**
>
> Inodes store vital metadata about files, the free list tracks available storage, and directory blocks manage the structure of directories. When we write to a file, we need to also update the inode to reflect the changes in the file!

Ensuring the reliability of file system writes requires that all associated operations, including both data and metadata block writes, are committed to disk. This commitment guarantees that the entire operation is successful and that the file system remains in a consistent state[2].

The problem arises from the nature of hardware operations. Each block write, whether for data or metadata, is executed as an individual hardware operation. This poses a challenge when multiple operations need to be synchronized to ensure the overall success of a write operation. Since data and metadata blocks might require separate writes, achieving the proper order and synchronization becomes complex.

19.4.2 Deferred Writes: Worst Case

Deferred writes (See **18.5.3 Write Caching**) can lead to a worst-case scenario in file system integrity when not managed correctly. This occurs when we allocate a new block to a file, writing out the updated inode immediately, but deferring the write-back of the free list. If a system crash occurs before the free-list updates are committed, a stale free list might exist upon reboot.

The trouble arises when a new process seeks a new block for a different file after the crash. Due to the stale free list, it's possible for the same block to be allocated to both files, resulting in shared block ownership.

This shared block can then lead to disastrous consequences: when one of the files is written, the shared block's content gets updated. Subsequently, when the other file is written, the same block's content changes again. This corruption cascade results in both files becoming corrupted due to the shared block's conflicting content updates.

19.4.3 Expectations

Recall that applications write to files via syscalls to the OS that encapsulate the process of writing data to storage media and handling associated metadata updates. After an application performs a write operation using a syscall, it expects that the data it wrote is $safe$[3]. This expectation is rooted in the desire for data consistency and durability, allowing applications and users to rely on the integrity of their stored information.

> **Example: Blocked**
>
> One approach involves blocking the writing application until the data is successfully stored, ensuring that it is indeed durable. However, this approach comes with a trade-off: it might lead to substantial delays, particularly if the storage process takes a considerable amount of time.

Additionally, we need to consider the rarity of system crashes. System crashes are relatively infrequent events[4]. Consequently, data persistence failures caused by crashes are also rare occurrences.

Striking the right balance between performance and safety is a critical consideration. Implementing safety measures to ensure data persistence is crucial, but it's equally important to avoid unnecessary

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[2]Without such commitment, the file system could end up in a situation where data and metadata are inconsistent, leading to potential data corruption or loss!

[3]Safe: All written data will persist even in the event of a system crash or unexpected shutdown.

[4]This assumes you don't have a dogshit computer.

performance degradation for scenarios that are statistically unlikely. Optimizing the system's behavior and employing techniques like caching and buffering can help manage this balance effectively.

19.4.4 Buffered Writes

Buffered writes represent a strategy in file systems where the persistence of written data is deferred to a later time, optimizing system performance and application responsiveness. Instead of immediately writing data to persistent storage, buffered writes involve tracking data in RAM buffers and providing early confirmation to applications that the write operation is successful.

> **Aside: Buffered v. Deferred Writes**
>
> To clarify, buffered writes temporarily hold data in a buffer before writing it to the storage media. Conversely, deferred writes involve delaying the actual writing of data to the storage media. Here, the data is initially written to a cache, where it is later flushed.

> **Corollary: Benefits and Issues**
>
> The primary benefit of buffered writes is that they minimize application blocking: by not requiring applications to wait for the actual write to complete before continuing, the overall responsiveness of the system improves. Buffered writes also enable the creation of deeper and more optimized write queues, enhancing the efficiency of write operations!
>
> Unfortunately, there is a notable downside to buffered writes: the potential risk of data loss. In the event of a system crash or unexpected shutdown between the time data is buffered in memory and the time it is actually written to persistent storage, there is a risk of losing the buffered data.

19.4.5 Ordered Writes

> **Definition: Ordered Write**
>
> **Ordered writes** refer to maintaining the sequence of write operations as they are issued by applications to ensure data consistency, preserving the expected order of updates even in the presence of caching and buffering mechanisms.

One key ordering principle is to write data before writing pointers to that data. Doing this allows the file system to identify unreferenced objects through garbage collection, which can later reclaim resources. Moreover, prioritizing the writing of data ensures that pointers point to consistent and accurate information, reducing the risk of issues caused by pointers leading to incorrect data.

Prioritizing the writing of deallocation information before new allocations contributes to system robustness. This strategy quickly releases resources associated with old files, allowing them to be reused. The free list can be corrected through garbage collection, which manages resource allocation more efficiently.

We care about ordered writes because while missing data can be addressed through recovery mechanisms, data sharing problems or inconsistent pointers can lead to more serious consequences that are harder to resolve.

> **Corollary: Practicality**
>
> While ordered writes are intended to enhance data integrity and robustness in file systems, their practical implementation involves significant trade-offs and challenges, more specifically I/O performance.
>
> The accumulation of nearby write operations, a common optimization technique, is eliminated with strict ordered writes. This results in diminished overall throughput as the file system lacks the ability to bundle similar write operations. Additionally, the consolidation of updates to the same block, which often improves efficiency, is hindered.
>
> Moreover, modern storage devices introduce additional complexity; they may reorder queued I/O requests at the hardware level, regardless of the order enforced by the file system. Consequently, even with strict ordering at the software level, the intended sequence of writes might be disrupted.
>
> Finally, ordered writes may not fully address the core problems they aim to solve. While they attempt to ensure a specific order of writes, they don't eliminate other issues that can compromise data integrity, such as incomplete writes.

19.4.6 Audit and Repair

Audit and repair strategies play a crucial role in enhancing file system robustness. To facilitate these strategies, file system structures should be designed with redundancy, storing redundant information in distinct locations for error detection and correction.

Auditing involves assessing the correctness and integrity of a file system. During this process, redundant information is utilized to detect errors, and the redundant data can be leveraged to perform automatic repairs when issues are identified.

> **Aside: Practicality**
>
> In the past, designing file systems with audit and repair capabilities was a common practice. Redundancy and error-correcting mechanisms were incorporated to ensure data reliability and integrity.
>
> However, practicality concerns have arisen with the growth of modern large-scale file systems. Thorough audits and comprehensive repairs are no longer feasible due to the immense storage capacities involved. Auditing a 2TB file system at a rate of 100MB/second, for instance, would take approximately 5.5 hours!

19.4.7 Journaling

> **Definition: Circular Journal**
>
> A **circular (buffer) journal** is a data structure used for maintaining a log of events related to file system operations to ensure data integrity and consistency.

Journaling is a technique in file system design that enhances data integrity and system robustness by ensuring that journal writes occur sequentially. It involves the creation of a circular buffer journaling device to facilitate efficient recording and execution of file system updates.

The use of a circular buffer means that once the buffer is filled, new journal writes begin overwriting the oldest records, creating a circular pattern. The circular nature of the buffer allows for the efficient use of limited space, as the oldest data is progressively replaced by new entries. Journal writes can also be batched together, which enhances efficiency by reducing overhead and optimizing the write process.

To improve performance and reliability, the journal may utilize a relatively small section of non-volatile RAM (NVRAM), ensuring that journal data can be quickly accessed and maintained even in the event of power loss.

The journal captures a comprehensive range of updates within the file system. This encompasses various changes, such as updates to inodes, block writes (data storage), and operations related to storage allocation and deallocation. By journaling these updates, the file system establishes a reliable mechanism for tracking modifications, making it possible to reconstruct the file system to a consistent state in case of failures, crashes, or abrupt system shutdowns.

Beyond data capture, journaling enables efficient scheduling of actual file system updates. Techniques like write-back caching, batching, and *motion-scheduling*[5] are used to enhance performance. These strategies reduce unnecessary overhead and delays, ensuring that updates are executed in an optimized manner.

After a write operation is successfully executed in the actual file system, the journal records a completion entry. This marks the point at which the intended updates are safely stored in persistent storage. The completion entry provides a synchronization point between the journal and the file system itself. In the event of a system failure or crash, the journal can be used to identify the most recent completed writes and apply them to the file system, ensuring that data remains consistent and accurate.

Aside: Batched Entries

Once a journal entry corresponding to an operation has been safely persisted, that operation is considered to be in a safe state. This means that the caller initiating the operation must wait until the journal entry has been successfully written to persistent storage. This process ensures that the file system maintains a consistent state even in the event of system crashes or failures.

Even with the safety provided by journal entries, the overhead introduced by the journaling process can impact the performance of small, frequent write operations.

To address the inefficiencies associated with small writes, a strategy is to accumulate journal entries in batches; rather than immediately persisting each individual journal entry, the system gathers multiple entries over a period of time. These entries are collected until either the batch reaches its capacity or a maximum waiting time is reached. Once the batch is considered complete, it is then written to persistent storage as a single operation.

This approach significantly reduces the overhead associated with frequent small writes, as the act of writing multiple entries at once is more efficient than writing them individually.

Recovery

Recall that the journal is a small circular buffer, and as such, it is designed to be recyclable, with older operations removed once they have been confirmed as completed. Time-stamps are assigned to entries in the journal, differentiating new operations from older ones.

The journal recovery process starts after a system restart or recovery from a failure. During this process, the entire journal is reviewed. Operations that are known to have been successfully completed are identified based on their time-stamps. Operations that lack confirmation of completion are re-executed[6] to ensure that their effects are properly integrated into the file system.

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[5]sequencing writes to minimize seek times.

[6]Journals are self-contained; i.e. both the data and the destination information for the write operation(s) are stored in the journal.

Once the recovery process is complete, the journal can be truncated, removing the entries that have already been successfully recovered. This prepares the journal for the capture of new operations, enabling the file system to resume normal operation while maintaining the integrity of stored data.

Corollary: Why Journaling Works

Journaling is an effective technique in file systems due to its inherent efficiency and design principles that enhance system reliability. Several factors contribute to the success of journaling in ensuring data integrity and swift recovery:

(i) Journal writes are notably faster than data writes because they are executed sequentially. Sequential writes optimize the write process, reducing the overhead associated with random access patterns.

(ii) The journal is write-only; the file system doesn't need to read or process the content of the journal under normal circumstances. This design choice simplifies the operation of the file system, focusing on capturing changes in a streamlined manner.

(iii) Scanning the journal after a restart or system failure is remarkably fast since the size of the journal is small compared to the size of the entire file system.

(iv) Journal pages may contain information related to multiple files; these pages often store information that pertains to various processes and users. This multi-file information organization is well-suited for capturing diverse changes across the file system, ensuring that updates from different sources are efficiently tracked and managed within the journal.

19.4.8   Metadata Only Journaling

Meta-data only journaling is a strategic approach in file systems that centers on capturing and journaling changes to meta-data while optimizing efficiency and data integrity. This method, despite some trade-offs, ensures the robustness of the file system's structure and operations.

Although metadata updates involve random I/O patterns, which are typically inefficient, they are crucial for maintaining the integrity of the file system. The small size of metadata entries makes it feasible to capture and store them within the journal, minimizing the impact of random I/O inefficiency.

The key factor that drives the decision to journal metadata is the potential for significant data loss in the event of a failure; by journaling metadata, the file system enhances its ability to recover from disruptions and maintain data consistency.

Conversely, journaling data itself is generally avoided due to several reasons.

(i) Data updates are often large and involve sequential I/O patterns, which are significantly more efficient than random I/O.

(ii) Due to its size, data would consume a substantial portion of the journal's capacity and bandwidth, potentially limiting the space available for capturing meta-data changes.

(iii) Data updates are less sensitive to order, allowing for more flexibility in the recovery process.

When data updates are required, the system allocates new space to accommodate these changes. The actual data updates are written to the newly allocated space, ensuring that the updated information is safely stored. Subsequently, the corresponding metadata updates that describe these changes are journaled. This two-step process guarantees that both the actual data and its associated metadata are reliably captured and preserved in the journal.

19.5   Log-structured File Systems

In RoW-based file systems, the traditional paradigm of repeatedly modifying blocks and inodes is replaced. Once written, blocks and inodes become immutable. Instead of overwriting existing data, new information is appended to a log. The file system's index is then updated to reflect these changes. This approach ensures that the original blocks and inodes remain untouched, providing a stable reference point for historical data.

One of the notable outcomes of this approach is the persistence of old versions of inodes and data within the log; if an older index is available, accessing these previous versions becomes feasible. This property also gives rise to the near-seamless creation of clones and snapshots of the file system. These operations become almost cost-free as they involve capturing references to specific points in the log.

However, the advantages of RoW come with certain considerations, particularly in the realm of management and garbage collection. As old versions of blocks and inodes remain within the log, maintaining an inventory of these historical elements becomes necessary. This management process ensures that file system operations, including retrieval of old data, proceed smoothly. Additionally, as the log accumulates data over time, the issue of garbage collection emerges. Reclaiming space occupied by outdated or unused log entries becomes essential to prevent wastage and maintain optimal storage efficiency.

Log-structured file systems represent a paradigm shift in file system architecture, where the journal itself forms the core of the file system. This innovative approach offers advantages and introduces challenges as it redefines how data and metadata are managed.

In log-structured file systems, all updates to inodes and data are directed to a sequential log structure. This log serves as the primary means of recording changes, and updates are typically implemented using the Redirect-on-Write (RoW) technique.

Instead of overwriting existing data, RoW involves writing the new data to a new location, leaving the old data intact. An in-memory index is maintained to cache the locations of inodes, allowing for efficient retrieval and modification.

Example: Flashpoint

This architecture has found significant adoption across various storage domains, and its dominance is particularly evident in flash file systems and key/value stores. The log-structured approach aligns well with the characteristics of flash memory, which performs more efficiently with sequential writes. Similarly, key/value stores that deal with high volumes of small, random writes benefit from the RoW technique's ability to optimize write patterns.

> **Corollary: Issues**
>
> In log-structured file systems, recovery time becomes a concern, as the in-memory index/cache must be reconstructed during recovery processes. This can potentially impact the time required to bring the system back to a functional state after a failure. Additionally, log defragmentation and garbage collection are inherent issues in this architecture; as the log accumulates updates, it can become fragmented, leading to suboptimal performance. Garbage collection is needed to manage the space occupied by outdated or invalid data, further impacting efficiency.

Chapter 20

Virtual Machines

Note In this chapter, "VM" will refer to "Virtual Machines" and **NOT** "Virtual Memory".

20.1 Overview

Definition: Virtual Machine

A **virtual machine (VM)** is a software-based simulation that is designed to closely mimic the behavior and characteristics of a genuine machine.

Virtual machines run an operating system, execute software applications, and perform tasks similar to those of a physical computer. Despite not being a tangible entity, a VM offers the appearance of a separate and autonomous system with its own resources and operating environment.

At its core, the concept of a virtual machine revolves around creating a software-based simulation that emulates the behavior of one or more distinct computers, all of which operate on a single *physical* machine. This involves leveraging the capabilities of an actual computer to facilitate the creation of multiple simulated environments. In essence, it's like having a computer within a computer!

Aside: What Do We Mean?

When we talk about virtual machines, we're referring to the practice of running multiple isolated instances of operating systems and applications on a single physical machine. These isolated instances are the virtual machines themselves. Each VM operates as if it were a separate, independent computer, complete with its own virtualized hardware resources, such as CPU, memory, storage, and network interfaces!

From the perspective of applications and users, the virtual machine must appear and behave like a real, individual computer. Each virtual machine can run its own operating system and host its applications, just as if they were on dedicated physical hardware.

This makes it possible to run multiple different operating systems on a single physical machine, which is particularly useful for scenarios like software testing, development, server consolidation, and cloud computing.

> **Corollary: Implementation**
>
> To achieve virtualization, a hypervisor (or virtual machine monitor [VMM]) is employed. The hypervisor manages the allocation of physical resources, such as CPU, memory, storage, and network interfaces, to the various virtual machines.
>
> The hypervisor presents each VM with a virtualized version of hardware resources that mirror the characteristics of real hardware components. However, these virtual resources are mapped to and implemented using the underlying real hardware!
>
> > **Example: Apples and Oranges**
> >
> > When a virtual machine's CPU executes instructions, it's the real physical CPU that processes those instructions, even though they pertain to the virtual machine's virtual CPU. Similarly, the data in virtual RAM is stored in the actual physical RAM, and data associated with virtual disks resides on real physical disks.

20.1.1 Why Virtual Machines?

Besides the fact that VM's are cool (IMO), there are many reasons for them:

(i) Fault Isolation: If one virtual machine encounters a software or hardware issue that causes a crash or malfunction, the impact is *contained* within that VM. This isolation prevents the problem from affecting other virtual machines on the same host or the host system itself. For critical systems and services, this isolation ensures higher reliability and uptime by minimizing the propagation of faults.

(ii) Better Security: Each VM operates within its isolated environment, isolated from other VMs and the host. This separation reduces the attack surface, making it harder for security breaches to spread across VMs. Even if one virtual machine is compromised, the isolation limits the attacker's ability to move laterally and access other VMs or the host. This security advantage is particularly valuable in environments where multiple applications with differing security requirements coexist.

(iii) Using Different OSes: The capability to run different operating systems concurrently on a single physical machine is a hallmark of virtual machines. Developers can leverage this feature for various purposes. It's especially useful for software development and testing[1]. This approach is also beneficial for maintaining legacy applications that require older operating systems, allowing them to run within a VM while using a modern OS on the host.

20.1.2 Fault Isolation

Fault isolation in virtual machines is a key advantage that allows operating systems to operate independently within their virtual environments. Unlike physical machines, where a crashing operating system could bring down the entire system, the isolation provided by virtual machines ensures that an OS crash affects only that specific virtual machine.

This relaxed requirement for perfect correctness, where a virtual machine can fail without causing the entire host to fail, enhances stability and robustness. This isolation also extends to faults that could damage devices; any damage or malfunction within a virtual device is contained within the virtual environment and does not impact the physical hardware.

20.1.3 Better Security

Virtual machines contribute to enhanced security by providing isolation between different virtual environments. While an operating system is responsible for securing processes within its domain, it also manages shared resources, such as the file system and inter-process communication (IPC) channels.

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[1]Developers can create distinct VMs for testing on various platforms without needing separate hardware for each OS.

Virtual machines offer the advantage of isolating these shared resources, ensuring that processes in one VM cannot easily access or damage resources in another VM. This isolation reduces the potential for security breaches and unauthorized access across virtual machines.

20.1.4 Different Operating Systems

Virtual machines enable running different operating systems on a single physical machine, overcoming compatibility issues between applications and their required environments. When an application requires a specific operating system with distinct system call interfaces, virtual machines provide an isolated environment that allows the desired operating system to run independently, ensuring compatibility and enabling the execution of applications that would otherwise face compatibility challenges.

> **Example: Looking into the Window of Linux**
>
> Suppose you are on a Windows host and want to run a Linux executable. Windows and Linux have different syscall interfaces and libraries, making it virtually impossible to run the Linux executable on bare metal Windows.
>
> However, with a Linux VM, we can create a self-contained environment that includes the Linux system call interface and libraries. When you run the Linux executable within the Linux virtual machine, it can make system calls and interact with the virtualized Linux environment as if it were running on dedicated hardware!
>
> The virtualization layer ensures that the Linux executable interacts with the Linux virtual machine's resources, while the Windows host remains unaffected. The virtual machine acts as a compatibility bridge, enabling applications to function correctly despite the differences between the underlying host and the required environment.

20.1.5 Sharing Resources

Virtual machines provide a practical solution for allocating and sharing resources among processes and applications. While an operating system can strive to control resource sharing among processes, it's often challenging to guarantee specific allocations. Variability in process demands, hardware capabilities, and changing workloads can make it difficult for an operating system to guarantee consistent and predictable resource sharing.

Virtual machines, on the other hand, offer a more reliable way to allocate resources. By assigning a predetermined allocation of resources to a virtual machine, the processes within it can be assured of their resource availability without impacting other virtual machines. This property is especially crucial in cloud computing environments, where multiple users and applications share the same physical hardware.

20.1.6 Running the VM

Running virtual machines involves executing their operations on real hardware. Ideally, virtual and real machines share the same ISA (See **1.5.1 Definitions**), simplifying execution. However, if they differ, performance may be compromised (more levels of indirection!). Virtual machine execution relies on direct execution whenever possible (See **7.3.4 Limited Direct Execution**), running VM activities directly on the CPU. When needed, virtual machine traps are used to switch from VM execution to the underlying host environment.

20.2   The Hypervisor

> **Definition: Hypervisor**
>
> The **hypervisor (virtual machine monitor [VMM])** is a controller that handles all virtual machines running on a physical machine.

Just as an operating system manages processes, the hypervisor manages virtual machines, ensuring their isolation, resource allocation, and efficient operation. Virtual machines run on top of the hypervisor, and they perform tasks just like any other software.

When a virtual machine's operations require interaction with the physical hardware or a privileged operation, we trap into the hypervisor. The hypervisor then performs the required action, which could involve tasks such as managing device access, handling I/O operations, or switching between virtual machines.

The hypervisor operates at a level lower than the guest operating systems within the virtual machines. It coordinates resource allocation, enforces isolation, and ensures that each virtual machine operates within its allocated resources. This enables efficient sharing of the underlying hardware among multiple virtual machines while preventing one virtual machine from negatively impacting others.

> **Corollary: VMM v. VM's OS**
>
> The VMM handles certain instructions that require privilege instead of allowing the VM to execute them directly for several reasons, including preventing unauthorized actions, ensuring resource allocation fairness, and maintaining overall system stability. The VMM's control over instructions allows it to make informed decisions about VM execution and resource utilization, even if the VM's operating system believes it's in control.

20.2.1   The Core Problem

The core challenge in virtualization arises from the separation of control between the VM's OS and the VMM. While the OS believes it has control over managing segregated virtual memories and their associated page tables for applications, the VMM ultimately controls critical aspects of memory management, including CPU registers pointing to page tables. This separation creates complexities in maintaining isolation, security, and resource allocation.

In a virtualized setup, each guest OS believes it has full control over its resources, including the management of segregated virtual memories for its applications. A key technique for achieving memory isolation is through the use of page tables. The OS maintains and manages these page tables, ensuring that each application operates within its allocated memory space.

However, the critical issue emerges when considering the management of CPU registers that point to these page tables. These registers determine how memory addresses are translated from virtual to physical addresses. While the guest OS *thinks* it controls these registers, the reality is that the VMM has the ultimate control over them.

This separation of control creates a complex scenario. The guest OS believes it's managing memory segregation and page tables for its applications, yet the VMM controls the underlying hardware mechanisms. When the guest OS tries to modify page tables or interact with CPU registers, it might be unaware that its actions are mediated or even overridden by the VMM.

This challenge becomes more apparent in scenarios involving memory protection, resource allocation, and security. The guest OS might attempt to segregate applications' memory spaces, enforce access controls, or allocate memory resources. However, the VMM could intervene, redirecting memory accesses or allocating resources differently to ensure fair resource sharing among multiple VMs.

20.2.2 Virtualizing Memory

> **Abstraction: Virtualizing Memory (Round II)**
>
> Virtualizing memory is a fundamental aspect of creating isolated environments for VM's while allowing them to operate as if they have direct access to physical memory. This illusion is achieved by introducing a layer of abstraction that involves both the VM's OS and the VMM.

From the perspective of the VM's OS, it believes it has access to its own contiguous address space of physical memory. The OS provides its processes with virtual memory addresses that map to locations within this contiguous address space. These virtual addresses are used by processes for memory operations, and the virtual OS maintains page tables to manage virtual-to-physical translations.

However, the physical memory addresses that the VM's OS and its processes use are actually *machine addresses*, and they are distinct from the actual physical memory addresses of the underlying hardware.

The VMM operates using the *machine addresses* that are specific to each VM. When the VMM receives memory access requests from a VM, it translates these machine addresses to actual physical memory addresses within that VM's assigned memory space.

Here, virtual-to-physical translation uses page tables and the paging hardware that the VMM shares with the VM's OS. The OS maintains its own page tables to map virtual memory addresses to machine addresses, and the VMM maintains additional page tables to map machine addresses to the true physical memory addresses!

> **Corollary: Outcomes**
>
> Virtualizing memory introduces various outcomes that impact performance. TLB misses (See **9.10.1 Big Page Tables**) become more costly due to transitions between privileged and unprivileged modes, resulting in increased overhead and system code execution. Additionally, the VM requires extra paging data structures, adding further overhead. As a result, virtual machines are likely to experience performance penalties due to these factors.

20.2.3 Better Performance

To improve the performance of virtual machines, various strategies can be employed. These include (but are not limited to):

(i) Special Hardware Features: Modern CPUs often include specialized hardware features[2] designed to address challenges associated with virtualization. These features help mitigate the performance overhead introduced by virtualization-related processes.

(ii) Paravirtualization: Unlike full virtualization, where guest OSes are unaware of the virtualization, paravirtualization requires certain modifications to the guest OSes. These modifications enable the guest OSes to communicate more directly with the VMM and take advantage of its services. This collaboration eliminates some of the overhead associated with virtualization.

20.3 Cloud Computing

Virtual machines play a crucial role in the context of cloud computing, where hardware resources are shared among multiple customers. Cloud providers offer computing power to customers, allowing them to run applications without dealing with the complexities of hardware management.

The cloud provider handles the underlying infrastructure and provides an environment for running virtual machines, which helps in efficiently utilizing hardware resources to serve multiple customers' needs.

Cloud providers act as intermediaries between hardware infrastructure and customers. They manage and maintain large data centers filled with servers, storage devices, and networking equipment.

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[2]e.g. Virtualization Extensions, I/O Virtualization, and MMU enhancements.

20.3.1   VM's in the Cloud

Virtual machines play a crucial role in cloud computing due to their ability to maximize hardware utilization, enable efficient resource sharing, and provide strong isolation between customers. By allowing multiple customers to run VM's on the same physical hardware, cloud providers can optimize resource usage, cater to diverse computing needs, and maintain stringent security and isolation.

However, efficiently placing VM's within a cloud environment involves addressing the challenge of distributing numerous VM's across physical nodes to optimize resource utilization. This often requires employing bin packing algorithms, which can be computationally complex due to their NP-hard nature. Estimation techniques are commonly used to tackle these complexities and achieve practical solutions.

20.3.2   VM Migration

VM migration is the process of transferring a running VM from one physical server to another within the cloud. The process must be *invisible*[3] and *fast*, ensuring uninterrupted service for users while maintaining the same functionality on the new server.

Moving a VM involves transferring a collection of data bits to another machine, resulting in an identical VM on the destination machine, provided both machines share the same architecture, memory, and other specifications.

> **Aside: The Issue**
>
> The bits within the VM keep changing due to running programs and system software updates on the original VM. Moving these bits across a network takes time, allowing for further changes to occur during the transfer process.

There are several approaches to remedy this complication:

 (i) Non-live migration: Freeze the VM during migration! Here, the bits won't change, but the VM won't run.

 (ii) Pre-copy live migration: Move the bits starting at one time, then iterate until there are no more changes. While the VM remains operational during migration (with minimal interruption), we may incur additional overhead since we copy modified bits multiple times.

(iii) Post-copy live migration: Initially move a minimum set of bits to the destination. The VM is then started on the new server with limited data, and additional bits are pulled over as needed from the source. Here, the VM is quickly started up in the destination server, but the initial startup may lack complete data.

Selecting the appropriate migration approach depends on factors such as the desired downtime, the nature of the VM's workload, network capabilities, and the tolerance for data inconsistencies during migration.

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[3]Invisible: There is no observable interruption of service.

Chapter 21

Security and Privacy

21.1 Overview

Operating systems serve as the foundational layer of software that users interact with. As such, if the operating system isn't protected, the machine isn't protected. Flaws in the OS generally compromise any and all security at higher levels.

The importance of OS security lies in its role in controlling crucial aspects of computer operation, including managing application memory, scheduling the processor, and allocating resources to users. A secure OS is essential for preventing a wide range of potential issues. In fact, many other security systems build upon the foundation of a secure OS.

21.1.1 Preface: Definitions

> **Definition: Security**
>
> **Security** encompasses a set of rules, guidelines, and objectives that dictate how a computer system or network should operate to maintain confidentiality, integrity, and availability of data and resources. These *policies* define what is allowed and what is restricted within the system.

> **Definition: Protection**
>
> **Protection** is the *mechanism* that ensures that the security policies are upheld.

Protection mechanisms are responsible for enforcing the security policies defined by an organization. These mechanisms include access controls, authentication processes, encryption, and other safeguards that prevent unauthorized users from accessing resources or data.

> **Definition: Vulnerability**
>
> A **vulnerability** is a weakness that can allow an attacker to cause problems.

> **Definition: Exploit**
>
> An **exploit** is the actual process of taking advantage of a vulnerability.

21.1.2 Trust

Trust is a fundamental concept in security, dictating actions and decisions based on confidence. It involves performing certain actions for entities or systems that are trusted and refraining from doing the same for untrusted ones.

A reoccuring theme throughout these notes has been that we *trust* our operating system, and that's because we're pretty much forced to; it controls all the hardware and memory, how our processes are

handled, handles I/O operations, and so much more. As such, if we cannot trust our operating system, we're pretty toast from the get go.

21.2 Authentication and Authorization

Definition: Authentication and Authorization

Authentication is the process of verifying the identity of a party seeking access.

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Authorization is the process of checking if the authenticated party should be allowed access. This is typically done after *authenticating* the party in question.

Authentication and authorization are important concepts in security, addressing the need to identify individuals or entities and grant them appropriate access privileges.

Security policies often grant specific privileges to certain parties while denying them to others. To enforce these policies, it's essential to identify who is making the request. This identification is typically performed by a computer within the operating system. The process of how computers achieve authentication is a key aspect of security.

Example: Real World Authentication

Let's look at some real world examples of authentication:

(i) Recognition: Seeing someone you know.

(ii) Credentials: Something like a driver's license.

(iii) Knowledge: What's the password to get into my tree fort?

(iv) Location: I'm behind the counter at the DMV.

Unfortunately, computers aren't as *smart*[1] humans as they lack the intuitive reasoning of humans. As such, they need a well-defined authentication process with a predetermined set of steps.

Computers are your guy when it comes to complex mathematical computations and processing large amounts of data quickly. This makes them particularly well-suited for cryptographic processes, where encryption and decryption involve intricate mathematical operations[2].

Authentication isn't limited to verifying human identity. Computers are often required to authenticate non-human entities as well, such as processes running on a system, network devices, or even automated software agents. Ensuring that these entities are authentic and authorized is crucial for maintaining the security and integrity of a computing environment.

21.2.1 Identities

Identities in operating systems typically revolve around user ID's, which uniquely identify individual users. When processes are executed, they inherit the user ID of the user initiating them.

Example: Forking ID's

A process created through forking inherits the same user ID as its parent process. This model implies that *any* process owned by a user inherits all the privileges associated with that user. While this approach has drawbacks, it is the predominant method used in operating systems.

21.2.2 Bootstrapping OS Authentication

Recall that when processes run within an operating system, they inherit the user ID of the user who started them. This enables processes to run with the user's privileges. However, when a new user logs

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[1]Smart: *Statistically*, computers are not as smart as humans.
[2]Computers are less likely to make simple mistakes compared to humans.

into the system, processes need to be created for them with the appropriate privileges. This process happens during login and marks the start of the user's session.

Unlike processes inheriting identity from parent processes, new users don't have existing processes to inherit from. To establish the identity of the new user, *authentication* is used during the login process to ensure that only authorized users access the system and that their processes operate with the correct identity.

21.2.3 Passwords

Passwords serve as a means of authenticating users based on something they know. To verify the correctness of the password, the system can either store the password itself or a hashed version of it[3]. If the provided password matches the stored (or hashed) password, the system associates the user's identity with a new command shell or window management process.

Corollary: Issues

Passwords, while widely used for authentication, come with several problems. They need to strike a balance between being difficult to guess yet easy to remember. Moreover, they are susceptible to *password sniffing*[a] on networked systems and *brute force*[b] entry on smaller passwords. Despite these challenges, passwords remain widely used, although they are considered outdated technology.

---
[a]where attackers intercept passwords as they travel across the network.
[b]`while (!correct) { try_again(); }`

21.2.4 Challenge/Response

Challenge/response systems are a form of authentication based on correctly answering predefined questions. Like passwords, this method relies on what we *knows*. The system presents questions to the user, and if they provide the correct answers, they are authenticated. This process is more secure if each challenge is unique, but might not always be practical.

Corollary: Hardware-based Challenge/Response

Rather than what we *know*, we can authenticate someone based on what we *have*. We can send a challenge to the hardware device belonging to the appropriate user expecting a response.

Example: Duo Push

When you log into MyUCLA, a Duo push notification is (usually) sent to your phone or other mobile device to verify that it's actually you logging in!

I still have yet to find someone that likes using Duo Push.

While challenge/response authentication offers improved security, it comes with its own set of problems. When based on what you know, there may be limited unique and secret challenge/response pairs, making the responses vulnerable to attackers.

Even if we authenticate based on what you have, there's a risk of impersonation by someone who possesses the required hardware. Additionally, certain challenge/response methods are susceptible to network sniffing, much like passwords. However, smart card implementations typically mitigate these risks.

21.2.5 Biometric

Biometric authentication is a method of authentication that relies on unique physical attributes of the user. It involves measuring specific characteristics such as fingerprints, voice patterns, or retinal

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[3]Storing a hash is a more secure approach.

patterns. These attributes are converted into binary representations and then compared against stored values. If the comparison yields a close match, the user is authenticated.

Unfortunately, biometric authentication usually requires *very* specific hardware. Not only that, many physical characteristics vary too much for practical, everyday use. Even if we solve the above issues, they're generally not helpful for authenticating programs or roles. Finally, we can have the possibility of false positives and negatives; i.e. you can impersonate someone else and we can't log into your own account respectively.

> **Corollary: Remote Authentication**
>
> Remember, the biometric reading is just a bit pattern. As such, if the attacker obtains a copy, he can just send the pattern over the network without performing an actual biometric reading! As such, the path between the reader and authentication device must be secure, which may raise problems when they are separated by the internet.

21.2.6 Multi-Factor

Multi-factor authentication is an authentication method that requires users to provide two or more separate forms of authentication to access a system or resource. This can involve combinations like a password and a text message to a cell phone. When implemented effectively, each factor compensates for the drawbacks of the other, providing a more secure authentication process. MFA is currently the preferred approach to authentication due to its ability to enhance security.

21.3 Access Control

> **Definition: Access Control**
>
> **Access control** refers to the operating system's ability to regulate which processes are permitted to access specific resources.

This capability enables the enforcement of security policies. The mechanisms employed by the operating system to enforce these policies, dictating who can access what, are collectively referred to as access control. This concept plays a crucial role in maintaining the security and integrity of an operating system.

21.3.1 Access Control List

Access Control Lists (ACL's) are a mechanism used in operating systems for managing and enforcing access control. Each protected object (e.g. a file or resource) is associated with a single list maintained by the OS. This list contains entries specifying which users or groups are allowed to access the object and the permitted modes of access. When a process or user requests access to an object, the OS checks the object's ACL to determine whether access should be granted.

> **Example: ACL's in Unix**
>
> ACL-based method for protecting files was developed in the 1970s and remains widely used today. In this approach, each file has its own ACL that specifies permissions for different subjects. For each file, there are three subjects listed: owner, group, and other. Each subject has three associated modes: read, write, and execute. This method allows for fine-grained control over file access and is still relevant in modern systems.

Advantages	Disadvantages
(i) Easy to figure out who has access. *(ii)* Easy to revoke/change access permissions.	*(i)* It may be hard to figure out what a subject can access. *(ii)* Changing access rights requires getting to the object.

21.3.2 Capabilities

The capabilities model involves entities maintaining a set of data items which specify their allowed accesses to resources. These capabilities function like tickets. To access an object, an entity presents the appropriate capability associated with that object. Possession of the capability signifies that access to the object is permitted.

It's important to note that capabilities are just data structures composed of bits, and having possession of a capability automatically grants access to the associated resource. Ensuring that capabilities are not forgeable is crucial. One solution to achieve unforgeability is to prevent users or processes from directly having the capabilities and instead store them within the operating system.

Advantages	Disadvantages
(i) Easy to determine which objects subjects can access. *(ii)* Potentially faster than ACL's. *(iii)* Easy model when it comes to transferring privileges.	*(i)* Hard to determine who can access an object. *(ii)* Requires extra mechanisms to allow for revocation. *(iii)* In a network environment, we need cryptographic methods to prevent forgery.

Corollary: OS Use

Operating systems commonly employ a combination of Access Control Lists and capabilities to manage access to resources. Sometimes, both methods are used for the same resource!

> **Example: Files**
>
> In Unix/Linux systems, *ACL's* are utilized during file opens to create a file descriptor with specific access rights. This file descriptor effectively functions as a *capability*, providing a way to access the resource with the authorized permissions.

21.3.3 Enforcing Access Control

Enforcing access control in an operating system involves ensuring that protected resources are inaccessible to processes unless granted access through proper mechanisms. Hardware protection mechanisms are used to prevent unauthorized access, ensuring that only the OS has access them.

To gain access, a process must issue a request to the operating system through a syscall. The OS consults its access control policy data to determine whether access should be granted. Access may be granted directly, with the resource being mapped into the process by a resource manager, or indirectly, where a *capability* is returned to the process by the resource manager.

21.4 Cryptography

Cryptography plays a crucial role in computer security by addressing the need to keep secrets confidential while allowing authorized parties to access them. It involves the use of controlled transformations on bit patterns to make it difficult for unauthorized individuals to read the secrets, while keeping it relatively simple for authorized parties to do so. Cryptography provides security advantages by ensuring data confidentiality, integrity, authentication, and more.

Aside: Terminology

Some terminology:

$$\begin{aligned}
S :=&\ Sender \\
R :=&\ Receiver \\
K :=&\ The\ secret\ key\ for\ en/decryption \\
Encryption :=&\ The\ process\ of\ making\ a\ message\ unreadable/unalterable\ by\ anyone\ but\ R \\
Decryption :=&\ The\ process\ of\ making\ the\ encrypted\ message\ readable\ by\ R \\
Cipher :=&\ Rules\ for\ transformations \\
Plaintext/P :=&\ The\ original\ message \\
Ciphertext/C :=&\ The\ encrypted\ message
\end{aligned}$$

$$\begin{aligned}
E() :=&\ The\ encryption\ algorithm \\
\implies\ C :=&\ E(K,P) \\
D() :=&\ The\ decryption\ algorithm \\
Cryptosystem :=&\ The\ system\ responsible\ for\ performing\ transformations\ on\ messages \\
\implies\ Cryptosystem :=&\ <E,D>
\end{aligned}$$

21.4.1 Cryptographic Keys

Most cryptographic algorithms use a secret key (K) to perform these operations. The key is a confidential piece of information. Decryption without the key is difficult, while decryption with the key is straightforward. Keys help reduce the problem of keeping a long message secret to keeping a short key secret, though there remains an essential element of secrecy.

21.4.2 Symmetric Cryptosystems

A cryptosystem is symmetric if and only if:

$$C = E(K,P)$$
$$P = D(K,C)$$
$$P = D(K,E(K,P))$$
$$C = E(K,P)$$

Note that $E()$ and $D()$ need not be the same operations.

Advantages	Disadvantages
(i) Encryption and authentication can be performed in a single operation.	(i) Hard to separate encryption from authentication, which can complicate some signature uses.
(ii) Well-known (and trusted) cryptosystems are much faster than asymmetric ones.	(ii) Non-repudiation is hard without servers.
(iii) No centralized authority required (though key servers help).	(iii) Key distribution can be a problem.
	(iv) Hard to scale, especially for internet use.

Example: Cipher Cipher Cipher!

Several popular symmetric ciphers have been developed for encryption and data protection purposes:

(i) The Data Encryption Standard (DES): A historic US encryption standard that is still used for legacy systems. However, it's considered weak by modern standards due to its small key size.

(ii) The Advanced Encryption Standard (AES): The current US encryption standard, widely used for its strong security and efficiency. AES is considered one of the most widely adopted symmetric ciphers.

(iii) Blowfish: A symmetric block cipher designed for increased security. While not as commonly used as DES or AES, Blowfish was well-regarded for its security features.

21.4.3 Brute Force Attacks

Symmetric ciphers can be vulnerable to brute force attacks, where attackers try every possible key until they find the correct one. The security of symmetric ciphers relies on the strength of their keys. Brute force attacks become increasingly difficult as the key length grows. Symmetric ciphers like DES (56-bit keys) are susceptible to modern brute force attacks due to their relatively short key length. However, AES (128 or 256-bit keys) is considered much more secure against such attacks due to its longer key lengths.

21.4.4 Asymmetric Cryptosystems

Asymmetric cryptosystems (public key cryptography [PK]), are cryptographic systems that utilize different keys for encryption and decryption. This allows secure communication and information exchange. Encryption is performed using a public key (K_E), and decryption is done using a corresponding private key (K_D). The process can also be reversed, where encryption is done with the recipient's public key and decryption with their private key.

Aside: Algebraic Representation

$$C = E(K_E, P)$$
$$P = D(K_D, C)$$
$$P = D(K_D, E(K_E, P))$$
$$\Longleftrightarrow$$
$$C' = E(K_D, P)$$
$$P = D(K_E, C')$$
$$P = D(K_D, E(K_E, P))$$

Public key cryptography involves the use of key pairs: a public key and a private key. These keys are created together and are used for encryption and decryption. One key (private key) is kept secret by the owner, while the other (public key) is shared with the world. This key-sharing mechanism enables secure communication. To send an encrypted message to someone, you use their public key for encryption, and only they possess the corresponding private key to decrypt the message.

21.4.5 Public Key Authentication

Authentication using public keys involves signing a message by encrypting it with your private key. This process ensures that only you, the owner of the private key, could have created the signed message. Everyone knows your public key, allowing them to directly verify your claim. This authentication mechanism is more secure than symmetric cryptography, as it guarantees that only the sender (owner of the private key) could have created the signed message, while the receiver (using the public key) can confirm its authenticity.

Corollary: Issues

Public key cryptography relies on the correct use of public keys for security. If an incorrect public key is used, the owner of that key could read your message or authentication might fail. Ensuring the right public key belongs to the intended person requires high assurance. This is achieved through key distribution infrastructures or certificates. Both methods, however, can pose challenges, especially at a large scale and in real-world scenarios.

Public key infrastructure (PKI) and certificate authorities (CA's) are used to address these issues; PKI provides a framework for managing public keys, while CA's issue digital certificates that bind public keys to entities. However, issues such as certificate revocation, trust in CAs, and the practicality of verifying certificates in real-world scenarios remain challenges.

Aside: PK Algorithms

PK algorithms are typically rooted in mathematical problems (e.g. factoring large numbers) that are hard to solve. The security of these algorithms relies less on brute force attacks and more on the inherent complexity of the underlying mathematical problems. This characteristic also results in the complexity and resource intensity of generating key pairs for public key cryptography.

Algorithms, such as RSA, ECC (Elliptic Curve Cryptography), and Diffie-Hellman, play a crucial role in securing online transactions, digital signatures, and secure communication. The security provided by these algorithms relies on the mathematical problems' inherent complexity, which remains an active area of research and development in cryptography.

21.4.6 Combining A/Symmetric Cryptosystems

The combined use of symmetric and asymmetric cryptography is a common approach to secure communication. Asymmetric cryptography is often used to "bootstrap" symmetric cryptography. This involves using asymmetric algorithms like RSA to authenticate and establish a secure session key, which is then used for the bulk of the data transmission.

The combined approach capitalizes on the strengths of both asymmetric and symmetric cryptography. Asymmetric cryptography is used where its unique features are most valuable (authentication, key exchange), while symmetric cryptography takes over for data encryption due to its efficiency. This hybrid approach balances the security provided by asymmetric cryptography with the performance benefits of symmetric cryptography, resulting in a comprehensive and effective security solution.

Chapter 22

Distributed Systems

22.1 Overview

Distributed systems are crucial in modern computing due to their prevalence in various applications. They are particularly relevant to operating systems because distributed systems are fundamentally a systems issue; even on a single computer, the OS needs to consider distributed issues. An understanding of distributed systems is essential for computer scientists to stay current and relevant in the field of modern computing!

22.1.1 Why Distributed Systems?

Distributed systems offer a myriad of benefits, some of which include:

(i) Better scalability and performance: Distributed systems allow applications to scale beyond the capacity of a single computer. By distributing resources and workloads across multiple machines, these systems can accommodate increasing demands for resources and bandwidth.

(ii) Improved reliability and availability: Distributed systems can maintain 24/7 service availability even in the face of hardware failures, disk failures, or software crashes. This redundancy and fault tolerance contribute to higher reliability and continuous service availability.

(iii) Ease of use, with reduced operating expenses: Centralized management of services and systems in distributed environments reduces the complexity of managing resources. Additionally, organizations can opt to purchase services rather than investing in physical computer equipment, leading to potential cost savings.

(iv) Enabling new collaboration and business models: Distributed systems enable collaborations that span geographical and organizational boundaries. They facilitate partnerships and collaborations on a global scale. New business models can emerge, offering a wide range of services in a global free market.

22.1.2 Issues

Distributed systems present several challenges due to the lack of shared memory and peripheral devices across machines. Interaction between machines relies on asynchronous and potentially slow and error-prone networks. Furthermore, failures of one machine may not be immediately visible to others, leading to synchronization and reliability issues. Addressing these problems requires solutions for remote communication, synchronization, fault tolerance, and reliable computation in distributed environments.

22.1.3 Transparency

Ideally, a distributed system should operate like a single machine system but with added benefits such as increased resources, improved reliability, and enhanced speed. Transparent distributed systems aim

to minimize the differences between single machine and distributed systems, providing users with a seamless experience that hides the underlying complexities of the distributed environment.

Transparency in distributed systems can manifest in various forms:

(i) Access Transparency: Users access resources (like files or data) without being aware of their location or distribution.

(ii) Location Transparency: Users are unaware of the physical location of resources or services.

(iii) Migration Transparency: Resources can be moved between machines without disrupting the user's experience.

(iv) Replication Transparency: Users are unaware of whether resources are replicated across multiple machines.

(v) Concurrency Transparency: Users can perform tasks concurrently, and the system handles coordination behind the scenes.

22.1.4 Deutsch's Seven Fallacies of Network Computing

Deutsch's "Seven Fallacies of Network Computing" highlight common misconceptions about networked and distributed systems. These fallacies underscore the challenges and complexities inherent in distributed systems. As a result, achieving true transparency in distributed systems, where the experience matches that of single-machine systems, is not practically achievable due to these inherent fallacies:

(i) The network is reliable: In reality, networks can experience outages, packet loss, and disruptions due to various factors. Relying on the network's absolute reliability can lead to system vulnerabilities.

(ii) There is no latency (i.e. instant response time): Latency, or the delay in data transmission, is a natural characteristic of networked systems. Achieving instant response times across distributed systems is challenging due to communication delays.

(iii) The available bandwidth is infinite: Bandwidth limitations are inherent in networks. While technology improves, bandwidth is not limitless, and congestion or high demand can lead to performance issues.

(iv) The network is secure: Ensuring network security is a complex endeavor involving encryption, authentication, and continuous monitoring. Networks are vulnerable to various threats, requiring ongoing efforts to maintain security.

(v) The topology of the network does not change: Networks can change due to hardware failures, reconfigurations, and scaling. Adapting to dynamic network changes is essential for resilient distributed systems.

(vi) There is one administrator for the whole network: Distributed systems often involve multiple administrators with varying levels of control. Centralized administration is not always feasible or practical.

(vii) The cost of transporting additional data is zero: Data transmission incurs costs, including infrastructure, bandwidth, and maintenance expenses. These costs can impact the efficiency and economics of distributed systems.

Understanding and accounting for these fallacies is essential for designing, developing, and managing effective distributed systems that deliver the intended benefits while acknowledging and addressing these inherent problems.

22.1.5 Paradigms

Distributed systems are approached through various paradigms[1] that address different aspects of their design and functionality:

(i) Parallel processing: This paradigm relies on tightly coupled special hardware to execute tasks simultaneously, aiming to achieve high computational performance. It involves breaking tasks into smaller parts that can be executed concurrently.

(ii) Single system images: This approach attempts to make all nodes in a distributed system appear as one large, cohesive computer from a user's perspective. Achieving a completely seamless single system image is challenging/impossible due to factors like communication latency and hardware differences.

(iii) Loosely coupled systems: In this paradigm, the focus is on working with the inherent difficulties of distributed systems as effectively as possible. Modern distributed systems often adopt this approach, acknowledging the need to address communication delays and potential hardware variations.

(iv) Cloud computing: A relatively recent development, cloud computing leverages distributed systems to provide on-demand computing resources over the internet. Users can access and use resources like processing power and storage without needing to own and maintain physical hardware.

22.2 Loosely Coupled Systems

Loosely coupled systems are characterized by a group of independent computers connected by a high-speed *local area network (LAN)*, where each computer serves similar but independent requests. These systems require minimal coordination and cooperation among the computers. They are motivated by scalability, price performance, availability (when using stateless servers), and ease of management.

Example: Couple of Loosers

Loosely coupled systems are used in a variety of applications, including (but not limited to):

(i) Web server clusters: Each server can independently handle incoming requests, distributing the load and improving performance.

(ii) Application servers: Multiple servers can handle application processing independently, contributing to better performance and responsiveness.

(iii) Cloud computing: Virtual machines/containers can be provisioned as needed, allowing users to dynamically scale their applications.

22.2.1 Loosely Coupled Architecture Elements

Loosely coupled architecture consists of several key elements that enable the design of distributed systems that are scalable, reliable, and manageable:

(i) Farm of Independent Servers: A collection of individual servers, each running the same software but serving different requests from clients. These servers are relatively independent and can handle requests concurrently.

(ii) Front-end Switch: An intermediary component that receives incoming client requests and distributes them among the available servers in the farm. This switch can perform load balancing to evenly distribute requests and failover to redirect traffic in case of server failures.

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[1]We won't be discussing *(i)* or *(ii)*.

(iii) Service Protocol: The communication protocol and design principles that guide the interaction between clients and servers in the farm (*stateless servers*[2], *idempotent operations*[3], and *successive requests*[4]).

22.2.2   Horizontal Scalability

Horizontal scalability is a design approach in distributed systems where each node operates largely independently, allowing capacity to be increased by adding nodes[5]. Horizontal scalability can be constrained by network limitations, rather than hardware or algorithms.

Reliability is generally high, as the failure of one out of many nodes doesn't significantly impact the overall system's capacity or performance. As such, horizontal scalability is particularly well-suited for modern applications that can leverage cloud computing and containerization technologies. It offers the ability to handle large-scale workloads and accommodate growth while maintaining reliability and performance.

Advantages	Limitations/Considerations
(i) Cost-effective: Adding commodity hardware nodes tends to be more cost-effective than upgrading individual nodes with more powerful hardware.	*(i)* Network bottlenecks: As the number of nodes increases, communication between nodes can become a limiting factor, impacting overall performance.
(ii) Enhanced performance: Distributing workloads across multiple nodes can lead to improved performance by reducing contention for resources.	*(ii)* Data consistency: Maintaining data consistency across multiple nodes can be complex, especially in scenarios where data is updated frequently.
(iii) Flexibility: New nodes can be easily added to accommodate growing workloads, making it suitable for dynamic and unpredictable demand.	*(iii)* Load balancing: Effective load balancing mechanisms are crucial to ensure even distribution of workloads and prevent overloading certain nodes.
	(iv) Application architecture: The application's architecture must be designed to take advantage of horizontal scalability, involving partitioning data and tasks appropriately.

Corollary: Performance

Horizontally scaled performance (via loosely coupled architectures) offers several advantages; low-cost individual servers, excellent scalability, and high service availability. Scalability and availability are enhanced by the ability to automatically bypass failed servers, the stateless nature of servers, and client retries for fail-over.

However, the challenge lies in managing a large number of servers, which requires automation in installation, global configuration services, self-monitoring, and self-healing systems. The scalability of these systems is limited not by hardware or algorithms, but rather by the thousands of servers we have to manage.

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[2]Stateless servers: Servers treat each request as independent, without relying on the state from previous requests.
[3]Idempotent: Re-executing the same operation multiple times does not result in unintended or undesirable outcomes.
[4]Successive requests to different servers: Clients may interact with different servers for successive requests, allowing for load balancing and dynamic resource allocation.
[5]This is often referred to as scaling "out" by adding nodes "on the side".