Operating Systems

Session 5: Concurrency and Synchronization

INTRODUCTION

Concurrency is a foundational principle in computer science, particularly within the realm of operating systems, where the management of multiple processes and tasks is essential for maximizing system performance. It refers to the ability of multiple processes or threads to execute simultaneously, allowing systems to perform several operations at once rather than executing one task at a time. This is crucial in modern computing environments, where applications need to handle multiple user requests, run background services, and efficiently utilize multi-core processors.

At its core, concurrency improves **system efficiency** by ensuring that the CPU and other resources are not idle. By overlapping the execution of processes, operating systems can enhance **parallelism**, allowing multiple processes to make progress at the same time, thus reducing latency and increasing throughput. For instance, while one process is waiting for input/output (I/O) operations to complete, another can use the CPU to perform calculations, ensuring that resources are continually in use. This is especially important in environments where many tasks must be performed simultaneously, such as web servers, real-time systems, and multi-user applications.

Despite its benefits, concurrency introduces a number of complex challenges. When multiple processes or threads access shared resources like memory, files, or hardware devices concurrently, they can interfere with each other in unpredictable ways. **Race conditions** arise when two or more processes access shared data or resources without proper synchronization, leading to unpredictable results that depend on the timing of their execution. For example, if two processes try to write to the same memory location at the same time, the final value could depend on which process finishes last, potentially causing inconsistent or corrupted data.

Another critical challenge is **deadlock**, where processes are stuck in a cycle of waiting, each holding resources that the others need to proceed. Deadlocks occur when certain conditions are met, such as mutual exclusion, where a resource can only be held by one process at a time and

circular wait, where processes form a closed chain of dependencies. In these situations, none of the processes can make progress, effectively halting system operations. Deadlock situations are particularly difficult to resolve because they often require manual intervention or a rollback of processes to a previous safe state.

To handle these problems, operating systems employ various **synchronization mechanisms** to ensure that processes and threads do not interfere with each other when accessing shared resources. One of the simplest mechanisms is the **mutex** (mutual exclusion), which ensures that only one process can access a resource at any given time, preventing race conditions. **Semaphores**, on the other hand, are more flexible synchronization tools that can be used to manage access to a limited number of resources. In addition, higher-level constructs like **monitors** are used to simplify synchronization by combining mutual exclusion with the ability to wait for certain conditions to be true.

Beyond these mechanisms, operating systems also implement strategies for **deadlock prevention, avoidance, and detection**. For example, algorithms like the **Banker's Algorithm** ensure that processes are only allocated resources if it's safe to do so, preventing the system from entering an unsafe state that could lead to a deadlock. In contrast, **deadlock detection algorithms** periodically check for cycles in the resource allocation graph and take corrective action, such as terminating one or more processes to break the deadlock.

In modern operating systems like **Windows** and **Linux**, these synchronization mechanisms are implemented using advanced primitives such as **mutexes**, **events**, and **critical sections** in Windows and **pthread_mutex** and **condition variables** in Linux. These primitives are essential for building robust, efficient multi-threaded applications that can take full advantage of today's multi-core processors and distributed computing environments.

With the increasing complexity of software and hardware architectures, the importance of understanding and effectively managing concurrency cannot be overstated. As systems continue to evolve, the ability to design and implement concurrency control mechanisms that prevent race conditions and deadlocks while ensuring efficient resource utilization is a critical skill for operating system developers and software engineers alike.

PROCESS CONCURRENCY

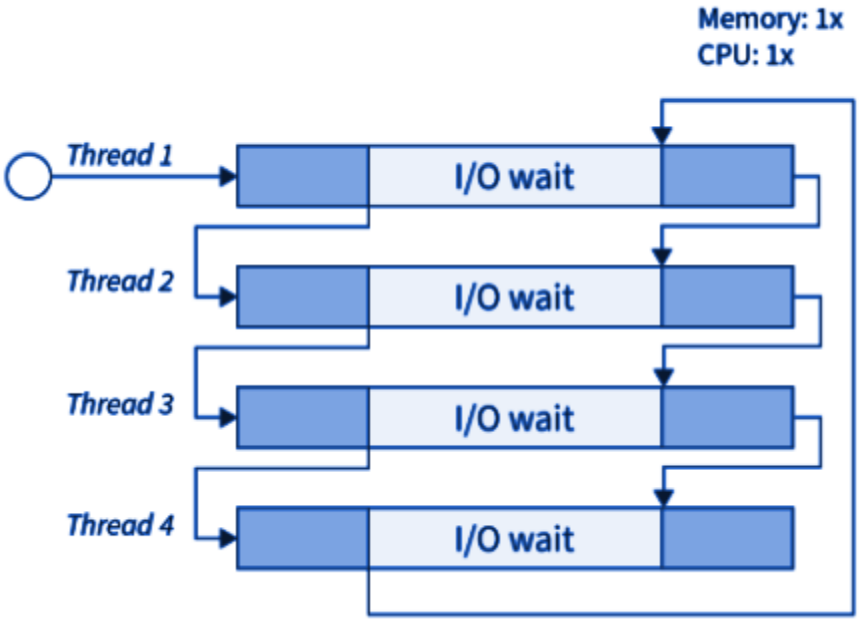
Process concurrency refers to the simultaneous execution of multiple processes or threads within an operating system. This is crucial in modern systems where multiple applications or tasks need to run in parallel to maximize resource utilization, increase performance, and improve responsiveness.

At its core, concurrency enables an operating system to overlap the execution of multiple processes. This can be achieved either through **true parallelism** (on multi-core processors,

where different cores execute different processes) or **interleaving** (on single-core processors, where the CPU switches between processes rapidly, giving the illusion of parallelism). While concurrency brings numerous advantages, it also introduces complexities in managing shared resources and ensuring consistent system behavior.

Concurrency in operating systems refers to the ability of an OS to manage and execute multiple tasks or processes simultaneously. It allows multiple tasks to overlap in execution, giving the appearance of parallelism even on single-core processors. Concurrency is achieved through various techniques such as multitasking, multithreading, and multiprocessing:

- **Multitasking** involves the execution of multiple tasks by rapidly switching between them. Each task gets a time slot, and the OS switches between them so quickly that it seems as if they are running simultaneously.
- **Multithreading** takes advantage of modern processors with multiple cores. It allows different threads of a process to run on separate cores, enabling true parallelism within a single process.
- **Multiprocessing** goes a step further by distributing multiple processes across multiple physical processors or cores, achieving parallel execution at a higher level.



Process concurrency refers to the ability of an operating system to execute multiple processes or threads simultaneously. This concept is essential in modern computing environments, especially in **multitasking** systems where the goal is to **maximize resource utilization**, enhance system **responsiveness**, and enable **parallel execution**.

Methods of achieving concurrency can be implemented in two primary ways:

- **True Parallelism**: This occurs in systems with **multi-core processors**, where each core can execute a separate process or thread simultaneously. Here, different cores handle different tasks in parallel, resulting in real-time execution of multiple processes.
- **Interleaving (Context Switching)**: In **single-core systems**, the CPU switches between processes so quickly that it gives the illusion of parallelism. The **operating system's scheduler** determines which process runs at any given time, managing these switches to ensure that all processes get a fair share of the CPU. The switching is fast enough that users perceive simultaneous execution.

Why Concurrency is Important?

Concurrency plays a critical role in the following areas:

- **Improved Resource Utilization: Input/Output (I/O) Operations**: Many processes, such as reading from a disk or waiting for network data, spend a lot of time idle while waiting for I/O to complete. During these periods, the CPU would be unused if there weren't other tasks ready to execute. Concurrency enables the CPU to switch to another process that can use the CPU while one process waits for I/O. This way, **no CPU time is wasted**, leading to better utilization of hardware resources.
- **Responsiveness: Interactive applications**, such as those with **graphical user interfaces (GUIs)**, rely heavily on concurrency to remain responsive. For example, while a file is downloading in the background, users still expect to click buttons, move windows, and interact with the interface without delay. Concurrency ensures that background tasks (like downloading) do not block **foreground tasks** (like responding to user input). This is vital for providing a **smooth user experience** in real-time systems.
- **Parallelism and Performance:** On **multi-core processors**, concurrency enables **true parallelism**, where multiple processes can run simultaneously on different cores. This **reduces execution time** and improves the overall throughput of the system.
  For example, a computationally heavy application like video rendering can be divided into multiple tasks, each handled by a separate core, thereby speeding up the rendering process.

Despite the advantages, **concurrency** introduces several **challenges** that need to be addressed:

Shared Resource Management

- Processes often share resources such as memory, files, or devices. Without proper coordination, concurrent access to these resources can lead to **race conditions**, **data corruption**, or **inconsistent behavior**. For instance, if two processes simultaneously attempt to modify the same memory location, the final result could be unpredictable.

Synchronization Issues

- To ensure that shared resources are accessed safely, processes need to be synchronized. **Mutual exclusion (mutexes)**, **semaphores**, and **monitors** are common mechanisms used to prevent multiple processes from accessing critical sections of code at the same time. Proper synchronization ensures **consistent and safe system behavior** but can lead to other problems, such as **deadlocks** or **starvation**.

Deadlocks and Starvation

- A **deadlock** occurs when two or more processes are waiting indefinitely for each other to release resources, creating a circular wait. **Starvation** occurs when a process is perpetually denied the resources it needs because other higher-priority processes are continuously favored. Techniques like **deadlock prevention** (e.g., **Banker's Algorithm**) and **fair scheduling** algorithms are used to manage these problems.

Techniques to Handle Concurrency include:

Synchronization Primitives

- **Locks and Mutexes**: These are used to enforce mutual exclusion, ensuring that only one process at a time can access a critical section of code or a shared resource.
- **Semaphores**: A semaphore is a signaling mechanism that can control access to shared resources by maintaining a counter to track the number of available resources. A **binary semaphore** (mutex) only allows one process to enter the critical section, while a **counting semaphore** can allow multiple processes depending on resource availability.
- **Monitors**: A higher-level abstraction than semaphores, monitors encapsulate both the data (shared resource) and the procedures (methods) that operate on that data, with automatic mutual exclusion.

Process Scheduling Algorithms

Continuing the course, we move on to **process scheduling**, a critical aspect of managing concurrency. Process scheduling determines how CPU time is allocated among processes and threads, ensuring **fairness**, **maximizing CPU utilization**, and **minimizing latency**.

1. Round-Robin Scheduling

- One of the simplest and most widely used algorithms is **Round-Robin**, where each process is assigned a fixed time slice called a **quantum**. Once a process's time expires, it is placed back in the queue, and the next process gets the CPU.
- The advantage is that no process is **blocked for too long**, and the system remains **responsive**.

2. Priority-Based Scheduling

- In this algorithm, each process is assigned a **priority**. The process with the highest priority gets access to the CPU. However, this system must prevent **starvation**, where lower-priority processes never get CPU time.
- To solve this issue, a **priority aging policy** can be used to gradually increase the priority of waiting processes.

3. First-Come, First-Served (FCFS)

- **FCFS** is the simplest scheduling algorithm, where processes are executed in the order they arrive. While easy to implement, this algorithm can suffer from the **convoy effect**, where a long-running process can block others from executing.

4. Shortest Job Next (SJN)

- **SJN** prioritizes processes with the shortest estimated execution times. This minimizes total execution time, but can struggle with the **uncertainty** of estimating each process's run time.

Resource Management and File Systems

After exploring process scheduling, we turn to **resource management** and **file systems**. These are crucial components of an operating system that impact **performance**, **reliability**, and **data security**.

1. Memory Management

- Modern systems implement **virtual memory management**, allowing programs to exceed the available physical memory. Techniques like **paging** and **segmentation** break memory into smaller, manageable blocks.
- Algorithms such as **Least Recently Used (LRU)** and **First-In, First-Out (FIFO)** are used to decide which pages should be swapped out of memory when they are no longer needed.

2. File Systems

- **File systems** manage the organization and storage of data on disks. They provide a **hierarchical structure** of directories and **file management**, enabling users and applications to access, modify, and share data efficiently.
- Modern operating systems like **Linux** and **Windows** utilize various **file system types** such as **NTFS**, **EXT4**, and **FAT32**, each offering specific features for security, performance, and compatibility.

Examples of Concurrency in Practice

- **Operating System Threads**: Both Windows and Linux use threads to implement concurrency at the operating system level. In **Linux**, threads are treated as lightweight processes (using the `clone()` system call), while **Windows** uses native thread management within its core APIs.
- **Web Servers**: Web servers like **Apache** or **Nginx** rely heavily on concurrency to handle multiple incoming requests simultaneously. They use threading models or event-driven architectures to ensure high performance and scalability.
- **Multithreaded Applications**: Applications like web browsers, where one thread may handle rendering, another handles network requests, and another handles user interactions, demonstrate the power of concurrency to improve responsiveness and performance.

Thus, **process concurrency** is crucial for modern computing systems to ensure better utilization of CPU, improved responsiveness, and faster execution times through parallelism. However, managing concurrent processes introduces challenges in resource sharing, synchronization, and scheduling, which require careful handling to avoid issues like deadlock and starvation. The tools and techniques provided by modern operating systems allow developers to harness the full potential of concurrency while maintaining system stability and performance.

CLASSIC CONCURRENCY PROBLEMS

In modern computing systems, where multiple processes and threads are executed simultaneously, ensuring smooth and efficient operation is a complex task. **Classic concurrency problems** are fundamental challenges that arise when processes or threads access shared resources concurrently. These problems often lead to conflicts, inconsistencies, or performance degradation if not managed properly. As systems become more complex, handling concurrency becomes critical to maintaining **system stability**, **performance**, and **data integrity**.

Concurrency problems stem from the difficulty in ensuring that processes are properly synchronized when accessing **shared resources** like memory, files, or I/O devices. Without proper management, concurrent access can lead to unpredictable system behavior, such as **race conditions**, where the outcome depends on the timing of process execution, or **deadlocks**, where processes are permanently stuck waiting for each other to release resources.

By studying and solving these classic problems, we can not only improve system reliability but also develop **robust synchronization techniques** that allow processes to **coordinate** their actions effectively. This helps in avoiding scenarios like **resource starvation**, where certain processes are perpetually denied access to resources, and ensures efficient and fair resource sharing.

Among the various challenges that arise in concurrent systems, two of the most critical, each presenting unique risks to system stability, are:

- **Race Conditions**
- **Deadlocks**

These issues can severely disrupt system performance, leading to **unpredictable behavior** and **instability** if not properly managed. Addressing them requires **careful synchronization**, proper allocation of resources, and precise **coordination** between processes, as both problems pose distinct risks to **system reliability** and must be handled with appropriate technique.

Example: **Multithreaded banking system**

Imagine a scenario in a **multithreaded banking system** where two processes, **Process A** and **Process B**, are responsible for updating the balance of the same bank account. The system involves multiple shared resources, including account balance data and logging information, and both processes need to access these resources to complete their tasks.

Race Condition Example:

- **Process A** reads the account balance of $1,000 from the shared memory to add $500.
- Before **Process A** can write the updated balance back to memory, **Process B** reads the same account balance of $1,000 to deduct $300.
- **Process A** writes the updated balance of $1,500 to the shared memory, followed by **Process B**, which writes $700 (after deducting $300).

As a result, even though both processes performed valid operations, the final balance in the account is incorrect because they both read the same initial value ($1,000) and didn't account for each other's updates, creating a **race condition**. The correct balance should have been **$1,200**.

Deadlock Condition Example:

Now consider that both **Process A** and **Process B** need access to two resources: the **account balance** and a **transaction log**. Each process needs both resources to complete their transaction:

- **Process A** locks the **account balance** and waits for the **transaction log** to be available.
- **Process B** locks the **transaction log** and waits for the **account balance** to be released.

In this situation, neither process can continue because they are both waiting for the other to release a resource, leading to a **deadlock**. Neither process can proceed, and the system is stuck until external intervention frees up the resources.

This example demonstrates how **race conditions** can lead to incorrect results due to improper synchronization, while **deadlocks** can cause system-wide stalling due to circular resource dependencies. Both issues require robust solutions such as locking mechanisms and deadlock detection/prevention strategies.

Example: **Concurrency Problem in a Web Application**

Below, we present a customized example from the professional activity of a software engineer, focused on web application development, to illustrate classic concurrency problems such as race conditions and deadlocks. This example reflects real-world scenarios you will encounter in your career when managing concurrent access to shared resources in high-traffic applications

Imagine you're developing a **web-based e-commerce platform**. Multiple users can place orders, update their shopping carts, and check out simultaneously. Two common concurrency problems—**race conditions** and **deadlocks**—can arise during this process if the system isn't properly synchronized.

Race Condition Example:

Consider two users, **User A** and **User B**, trying to purchase the **last item in stock** simultaneously. Both users add the item to their shopping cart, but there's only **one unit** available.

- **User A's** process checks the available stock (1 item) and decides to proceed with the purchase.
- Meanwhile, **User B** also checks the stock at the exact same moment, sees the 1 item available, and attempts to purchase it.
- Without proper locking mechanisms to prevent concurrent access, both users might end up purchasing the item, which results in **overselling**, even though only one unit should have been sold. This is a **race condition**—the outcome depends on which user's request is processed first.

Solution: Implement **atomic transactions** and proper locking mechanisms to ensure that once a user starts the checkout process, the stock is adjusted immediately, preventing other users from accessing the same stock at the same time.

Deadlock Condition Example:

Now, let's assume the web application needs to update two shared resources during the checkout process: the **inventory database** and the **payment gateway**.

- **User A's transaction** locks the inventory database first to adjust stock, then waits for the payment gateway to complete the transaction.
- At the same time, **User B's transaction** locks the payment gateway to validate payment and waits for the inventory database to be updated.

In this case, neither transaction can proceed because **User A** is waiting for the payment gateway, which is locked by **User B**, and **User B** is waiting for the inventory database, which is locked by **User A**. This results in a **deadlock**, where both processes are stuck indefinitely.

Solution: Implement **deadlock prevention** strategies, such as requiring processes to always lock resources in a predefined order (e.g., lock the inventory database first, then the payment gateway). Alternatively, use **timeouts** or **deadlock detection** algorithms to detect and resolve the issue by rolling back one of the transactions.

Both problems emphasize the need for synchronization mechanisms like mutexes, semaphores, and condition variables to ensure safe, consistent access to shared resources in multi-threaded environments. Thus, **classic concurrency problems** like **race conditions** and **deadlocks** emerge when processes or threads simultaneously compete for shared resources. **Race**

conditions lead to unpredictable results due to overlapping operations, while deadlocks cause processes to become stuck, waiting on each other indefinitely. These issues underscore the importance of using synchronization tools, such as mutexes and semaphores, to manage concurrent access effectively and maintain system stability.

RACE CONDITIONS

A **race condition** occurs when two or more **processes** or **threads** attempt to access and modify shared resources—such as **memory**, **variables**, or **files**—simultaneously without proper synchronization. In such cases, the outcome of operations depends on the **order** or **timing** of the processes' execution. Since this sequence of execution can vary, the system may produce **unpredictable results**, leading to **inconsistent** or **incorrect program behavior**. Race conditions are especially problematic in **multi-threaded** and **multi-processor systems**, where the concurrent execution of processes makes the timing of operations **non-deterministic**, i.e., it's impossible to predict in what order the operations will happen.

Race conditions occur when multiple threads or processes race to access a shared resource, and the outcome depends on which process finishes first. This unpredictability makes race conditions extremely dangerous because they can lead to **data corruption**, **inconsistent states**, and **system crashes** if not properly handled.

How Race Conditions Happen:

Race conditions arise when:

1. **Multiple processes** or threads **access and modify shared resources simultaneously** without coordination.

Example: Two threads reading and writing to the same memory location at the same time without using locks or synchronization.

2. There is a **lack of proper synchronization mechanisms** (such as locks, semaphores, or mutexes) between processes, allowing concurrent access to shared data.

Example: A database query being updated by multiple threads without a transaction or lock in place to manage access.

3. In **time-sharing** or **multi-threaded environments**, parallel execution creates uncertainty in the exact **order of operations**, making it difficult to predict when each process will access or modify the shared resource.

Example: In a web server, two clients may try to update the same record in a database, and the final state of the data depends on which client's transaction is processed last.

4. In **multi-core systems**, the risk is even greater because processes or threads might run on **different processors** at the same time, increasing the complexity of managing concurrent access. However, even in **single-core systems**, where time-slicing (rapid switching between processes by the operating system) occurs, race conditions can still happen, since the order of execution can still vary between processes.

Example: In a system where multiple cores execute threads in parallel, one thread could be modifying a shared variable while another thread on a different core reads that variable, leading to inconsistent data if not synchronized.

5. Even in **single-core systems**, where **time-slicing** (rapid switching between processes by the operating system) occurs, race conditions can still happen, since the **order of execution** can still vary between processes.

Example: Even though only one thread is active at a time, switching rapidly between them without coordination can still lead to conflicting reads and writes.

Example of a Race Condition:

Consider two banking applications that both attempt to modify the balance of the same account at the same time. Without proper synchronization, one process could read the account balance before the other process has updated it, leading to a discrepancy in the final balance. This can result in **inconsistent data**, such as missing transactions or incorrect balances—classic symptoms of a race condition.

Consider a simple example where two processes, P1 and P2, both increment a shared counter variable. The increment operation involves three steps:

1. **Read** the current value of the counter from memory.
2. **Increment** the value by 1.
3. **Write** the updated value back to memory.

Here's what the code might look like:

```
// Shared variable

int counter = 0;

void increment() {

    counter++;  // Increment shared counter

}
```

- **Process P1** reads the current value of `counter` (0), increments it to 1, and prepares to write 1 back to memory.
- **Process P2** also reads the current value of `counter` (0) before P1 finishes writing, increments it to 1, and writes 1 back to memory.

At the end of this execution, the counter holds the value **1**, even though both processes incremented it. The correct final value should be **2**, but since the processes accessed and modified the shared variable at the same time, they both read the same initial value of **0**, leading to a race condition.

Another example of a Race Condition:

Imagine you're developing a **social media platform**, and two users simultaneously update the same **profile information**—one user changes the profile picture, while the other updates the bio.

- **Thread A** starts reading the user's data and modifies the **profile picture**.
- **Thread B** starts reading the same user's data at almost the same time and updates the **bio**.

If both threads attempt to write their updates back to the database without synchronization, one of the updates may get **overwritten** by the other. In this case, the final state of the profile will only reflect the last write, leading to **data loss** or **inconsistent profile information**.

To prevent this, you need to implement **synchronization mechanisms** like **transactions** or **locking** to ensure that only one thread can write to the user profile at a time.

Preventing Race Conditions:

Race conditions can be avoided using several techniques:

1. **Locks (Mutexes)**: Ensure that only one process or thread can access a shared resource at a time.

Example: Using a mutex to ensure only one thread can write to a shared memory location.

2. **Atomic Operations**: Guarantee that certain operations happen as a single, indivisible action.

Example: Incrementing a counter using an atomic function that prevents other threads from interfering.

3. **Semaphores**: A synchronization tool that controls access to resources by maintaining a count of how many processes can access the resource.

Example: Limiting access to a shared resource to a fixed number of threads, ensuring safe access.

4. **Monitors**: Higher-level synchronization tools that provide an abstraction over locks and condition variables to safely manage shared resources.

Example: A monitor that manages access to a queue, ensuring threads can add or remove items without causing data corruption.

Consequences of Race Conditions:

1. **Inconsistent Data:**
    - Race conditions can corrupt data, as seen in the example where the shared counter was supposed to be incremented twice but ended up with an incorrect value.
    - This issue is particularly dangerous in scenarios such as financial systems, where inaccurate calculations or records can lead to incorrect transactions, lost data, or system failure.
2. **Unpredictable Behavior:**
    - One of the most difficult aspects of race conditions is that they lead to **non-deterministic** behavior. The result of the race condition might vary between runs, depending on the exact timing of the processes. This makes race conditions notoriously hard to reproduce and debug.
    - For example, a race condition may not manifest every time the code is executed, which leads to **intermittent bugs**.
3. **Security Vulnerabilities:**
    - Race conditions can create serious security risks. For instance, in a scenario where a system first checks user permissions before performing an operation, a malicious process could exploit a race condition to modify the permissions between the check and the operation, gaining unauthorized access to sensitive resources.
    - These vulnerabilities, known as **TOCTOU (Time Of Check To Time Of Use)** bugs, often appear in systems where resource access checks are not properly synchronized.

Example:

A process checks if a file is readable before opening it:

```
if (access("/file", R_OK)) {
    // File is readable, proceed to open
    open("/file", O_RDONLY);
}
```

4. A malicious process could change the permissions of `/file` between the check (`access`) and the open operation, allowing unauthorized access.

Challenges in Detecting Race Conditions:

1. **Non-deterministic Behavior:** Race conditions are often difficult to detect because their occurrence depends on the precise timing of concurrent processes, which can vary with each run of the program.
2. **Timing Sensitivity:** A race condition might only occur under very specific conditions or loads, such as on heavily utilized systems or during rapid context switching between threads. This makes it challenging to test for race conditions during regular development and testing.
3. **Intermittent Failures:** As race conditions don't necessarily cause failure every time, they can lead to intermittent bugs that are difficult to trace, often only appearing under heavy system load or specific execution paths.

Solution to Race Conditions:

To prevent race conditions, it's essential to use synchronization mechanisms that enforce **mutual exclusion**, ensuring that only one process can access the shared resource at a time. Here are some common solutions:

Locks and Mutexes: A **mutex** (mutual exclusion object) is a synchronization primitive that allows only one process to hold the lock at a time, preventing others from accessing the shared resource until the lock is released.

Example with Mutex:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

void increment() {

    pthread_mutex_lock(&lock);   // Acquire the lock

     counter++;                      // Critical section: safe to modify shared
resource

    pthread_mutex_unlock(&lock); // Release the lock

}
```

1. In this example, `pthread_mutex_lock` ensures that only one process can access the shared resource (in this case, the `counter`) at a time. Once the process finishes updating the counter, it releases the lock so that other processes can safely access the resource.
2. **Semaphores:** A **semaphore** is another synchronization mechanism, which can be either binary (like a mutex) or counting, allowing more complex resource management. Semaphores maintain a count that indicates how many processes can access the resource at the same time.
    - **Binary Semaphore**: Acts like a mutex, allowing only one process to access the critical section.
    - **Counting Semaphore**: Allows multiple processes to access the resource simultaneously, but limits the number of processes that can do so.
3. **Monitors:** A **monitor** is a high-level synchronization construct that ensures mutual exclusion and provides condition variables to allow processes to wait for certain conditions to be true. Monitors are often built directly into high-level programming languages like Java and are easier to use than raw locks or semaphores.

Atomic Operations: Atomic operations are indivisible operations that complete without any interruption. By using atomic operations, processes can perform critical modifications to shared data in a single, uninterruptible step, preventing race conditions.

Example – Test and Set:

```
bool test_and_set(bool *lock) {

    bool old_value = *lock;
```

```
    *lock = true;

    return old_value;

}
```

4. This function atomically checks if the lock is available and sets it if it is. If two processes attempt to access the shared resource at the same time, only one will succeed in acquiring the lock.

5. **Condition Variables: Condition variables** are used in conjunction with mutexes to allow threads to wait for certain conditions to be true before proceeding. They help manage complex interactions between threads and ensure that shared data remains consistent.

Race conditions are a significant problem in concurrent programming that can lead to data corruption, unpredictable behavior, and even security vulnerabilities. To manage race conditions, operating systems and programming languages provide various synchronization primitives like **mutexes**, **semaphores**, and **atomic operations**. By enforcing mutual exclusion and coordinating access to shared resources, developers can ensure that concurrent processes interact in a predictable and safe manner, thus avoiding the pitfalls of race conditions.

DEADLOCKS

A **deadlock** occurs when a set of processes becomes permanently stuck, each waiting for a resource that is held by another process in the set. None of the processes can proceed because they are mutually dependent on each other to release the resources they need, creating a **cycle of dependency**.

In other words, each process is holding a resource and waiting for another one, while the other processes are doing the same, causing all of them to be **blocked indefinitely**.

Deadlocks are especially problematic in **multi-threaded** and **multi-process systems**, where processes frequently need to access shared resources like memory, files, or hardware devices. When deadlocks occur, they can bring an entire system or application to a halt, leading to severe consequences such as **data loss**, **performance degradation**, or even **system crashes**. The processes caught in a deadlock will never release their resources, which means external intervention is often required to resolve the situation.

These issues are critical in systems that require **high availability** and **reliability**, such as databases, operating systems, and network servers. Understanding how deadlocks happen, and implementing strategies to **detect**, **prevent**, or **recover** from them, is essential to maintaining stable and efficient system performance.

Consider a **printer sharing system** in an office. Process **P1** is using the printer (Resource **R1**) to print a document, while it waits for **access to a scanner** (Resource **R2**) to scan some files. At the same time, Process **P2** is using the scanner (**R2**) and is waiting for **access to the printer** (**R1**) to print its scanned documents. Both processes are now in a deadlock because:

- **P1** holds **R1** (printer) and waits for **R2** (scanner).
- **P2** holds **R2** (scanner) and waits for **R1** (printer).

Neither process can complete its task because they are **stuck waiting for each other**, creating a deadlock. Without intervention, this situation would persist indefinitely, halting both operations.

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Conditions for Deadlock

For a **deadlock** to occur, a specific set of conditions must be present. These are known as the **Coffman conditions**, which describe the prerequisites that allow deadlocks to form. Deadlocks can only happen when all four of these conditions hold **simultaneously**. Understanding these conditions is essential for devising strategies to **prevent** or **detect** deadlocks before they impact system performance. Let's break down these four conditions:

1. **Mutual Exclusion:**
    - For a deadlock to occur, at least one resource must be **non-shareable**, meaning it can only be held by **one process** at a time. This is called **mutual exclusion**. For example, if a process is using a **printer**, no other process can access the printer until the first process finishes using it and releases the resource. Mutual exclusion is essential for managing **critical resources** but also sets the foundation for potential deadlocks because it restricts access, creating a scenario where other processes are forced to wait.

Example: A **printer** can only be used by one process at a time. If **Process A** is printing a document, no other process can access the printer until Process A has completed its job and

released the printer. Any other process trying to print at the same time will have to wait for the printer to become available. This exclusivity is critical to avoid printing errors, but it also introduces the possibility of a deadlock if other conditions are met.

2. **Hold and Wait:**
    - The **hold and wait** condition occurs when a process is holding onto at least one resource while simultaneously **requesting additional resources**. The process continues to hold its current resources while waiting for the new ones to become available. This can lead to **resource blocking**, where processes are stuck waiting for resources that are being held by other processes. An example would be a process that holds a **file lock** and then requests access to a **network connection** while still holding the file lock, causing a delay for other processes that need that file.

Example: Imagine a **file editing program** (Process B) that holds a lock on a file and then requests access to a **database connection** to save updates. At the same time, another process (Process C) holds the database connection and requests the file lock to read from it. Both processes are holding resources and waiting for others, leading to a hold and wait situation. If neither process releases its current resources, they could be stuck waiting indefinitely.

3. **No Preemption:**
    - The **no preemption** condition means that once a process has acquired a resource, it **cannot be forcibly taken away** by the operating system or another process. The resource can only be released voluntarily by the process that holds it, after the process completes its task. This guarantees that processes retain control over resources for as long as they need them, but it also leads to potential deadlocks, as resources may remain locked indefinitely. For instance, a process using a **database lock** cannot be interrupted or forced to release the lock until it has finished its transaction.

Example: Consider a **video processing application** (Process D) that is writing large video files to a **disk drive**. Once the process starts, the disk resource is locked until the write operation is complete. If another process (Process E) needs access to the disk to store data, it cannot force Process D to release the disk prematurely. Process E must wait until Process D finishes its task. In a deadlock scenario, if Process E is holding another resource that Process D needs, neither can proceed, causing a deadlock.

4. **Circular Wait:**
    - The **circular wait** condition occurs when there is a closed chain of processes, each of which is holding at least one resource while **waiting for another**

resource that is being held by the next process in the chain. This creates a **circular dependency** where no process can proceed because they are all waiting on each other. For example, **Process A** is holding **Resource 1** and waiting for **Resource 2**, which is held by **Process B**, while **Process B** is holding **Resource 2** and waiting for **Resource 1**, creating a cycle that leads to a deadlock.

Example: Imagine **Process F** is holding **Resource 1** (e.g., a CPU lock) and waiting for **Resource 2** (e.g., a memory lock). At the same time, **Process G** holds **Resource 2** and is waiting for **Resource 1**. This creates a cycle where neither process can proceed, as each one is waiting for the other to release a resource. This cycle can involve more than two processes, forming a larger deadlock loop where every process is waiting on a resource held by the next one in the chain.

Example of Deadlock:

Deadlocks can occur in real-world systems when processes compete for a limited number of resources, creating a situation where none of the processes can proceed. Let's explore a classic example involving two processes, **P1** and **P2**, and two critical resources, **R1** and **R2**. These resources are essential for each process to complete its task, but improper management of resource allocation leads to a **deadlock**.

Consider two processes, **P1** and **P2**, and two resources, **R1** and **R2**:

1. **P1** holds **R1** and requests **R2**.
2. **P2** holds **R2** and requests **R1**.

This creates a deadlock because:

- **P1** cannot proceed until it gets **R2**, but **R2** is held by **P2**.
- **P2** cannot proceed until it gets **R1**, but **R1** is held by **P1**.

Neither process can make progress because each is **waiting for the other to release a resource**. As a result, they are both stuck in a **cycle of dependency**. This deadlock situation can persist **indefinitely**, freezing both processes and, without external intervention, halting any progress in the system.

Consequences of Deadlocks

Deadlocks can have significant and wide-reaching impacts on the stability and efficiency of systems, especially in environments that rely on high availability. Below are some of the critical consequences of deadlocks:

1. **System Hang:**

- In a deadlock, the processes involved become permanently blocked, unable to proceed. This can cause the entire system or application to **freeze** if critical resources like **memory**, **CPU cycles**, or **I/O devices** are involved. When these resources are held indefinitely by the deadlocked processes, other processes that need access to them are also blocked, leading to a **system hang**. In a multi-user or real-time system, this can result in a complete stoppage of all active processes, requiring manual intervention, such as a system reboot or killing the affected processes, to restore normal operations. In mission-critical systems, this can be disastrous.

2. **Resource Wastage:**
    - When deadlock occurs, the resources held by the blocked processes are **allocated but not being used productively**. Since the deadlocked processes cannot release these resources, they become unavailable to other processes that might need them. This causes a **cascading effect**, where more processes get blocked waiting for those resources, resulting in **system-wide inefficiencies**. For instance, in a database system, a deadlock involving multiple transactions can lock tables or files indefinitely, preventing other transactions from accessing them, which severely degrades system performance.
3. **Service Downtime:**
    - In systems like **web servers**, **cloud platforms**, or **database management systems**, deadlocks can lead to prolonged **service outages**. For instance, if a deadlock occurs in a high-traffic web server, critical services could stop responding, leading to **downtime**. This is especially problematic for businesses that rely on these systems for continuous operation. The **financial consequences** of downtime can be significant, especially in industries where uptime is crucial, such as **e-commerce**, **banking**, or **telecommunications**. In such cases, the deadlock may need immediate intervention to prevent lost revenue, damaged reputation, or breached service-level agreements (SLAs).

Deadlock Modeling and Detection

To effectively understand and manage deadlocks, we can use a **resource allocation graph** to visually model how processes and resources interact. This approach helps in both **predicting** and **detecting** deadlocks by illustrating the flow of resource requests and allocations. Let's break down how this works:

Resource Allocation Graph Components:

- **Processes** are represented as **nodes** (circles), each corresponding to an active process in the system.
- **Resources** are also represented as **nodes** (squares or rectangles), representing individual resources (e.g., memory blocks, printers, or files).

Edges in the Graph:

- **Directed edges** (arrows) show the relationship between processes and resources:
    - An arrow from a **process to a resource** indicates that the process is **requesting** the resource. For example, if **Process P1** requests **Resource R1**, there is an edge from **P1** to **R1**.
    - An arrow from a **resource to a process** indicates that the resource is **allocated** to that process. For instance, if **R1** is currently assigned to **P2**, the edge goes from **R1** to **P2**.

Cycles Indicating Potential Deadlocks:

One of the key features of a resource allocation graph is the ability to **identify cycles**, which indicate the potential for a deadlock.

- A **cycle** in the graph forms when a group of processes is involved in a circular dependency:
    - **Process P1** holds **Resource R1** but is waiting for **Resource R2**.
    - **Process P2** holds **Resource R2** but is waiting for **Resource R1**.
    - This forms a **cycle** in the graph, visually representing the **circular wait** condition, a key indicator of a potential deadlock.

A **cycle** in the resource allocation graph indicates the potential for a deadlock. If there is a cycle and all processes in the cycle are waiting for resources, a deadlock has occurred.

Deadlock Detection Algorithms:

- **Wait-for Graph**: A simplified version of the resource allocation graph where only processes are nodes, and an edge from **Process A** to **Process B** means that **A is waiting for a resource held by B**. Detecting a cycle in this graph indicates a deadlock.

- **Banker's Algorithm**: This is used to detect and prevent deadlocks by checking whether granting a requested resource would leave the system in a safe state. If it would lead to a deadlock, the resource is not allocated.

Real-World Application:

For example, in a **database management system**, where multiple transactions need access to the same tables or data records, a resource allocation graph can help detect situations where two or more transactions are waiting for each other to release locks on the same resources, leading to a deadlock. Early detection through these graphs can help mitigate issues before they escalate to a complete system block.

Deadlock Solutions

There are three primary approaches to handling deadlocks: **prevention**, **avoidance**, and **detection and recovery**. Each approach focuses on different methods to either **avoid** deadlocks from occurring in the first place, **detect** them when they happen, or **recover** from them once they occur. Let's explore each approach in more detail:

1. **Deadlock Prevention:**

Deadlock prevention focuses on eliminating one or more of the **Coffman conditions** (mutual exclusion, hold and wait, no preemption, circular wait), which are necessary for a deadlock to occur. By ensuring that at least one of these conditions cannot hold, deadlocks are prevented from forming.

Strategies for Deadlock Prevention:

- **Mutual Exclusion**: In systems where possible, resources should be made **shareable** to avoid mutual exclusion. For instance, read-only files or databases can be accessed by multiple processes simultaneously, removing the need for exclusive locks. However, certain resources like printers or hardware devices cannot be shared, so this is not always feasible.
- **Hold and Wait**: This strategy requires processes to **request all the resources they need upfront**. By doing so, processes cannot hold onto some resources while waiting for others. Although this approach reduces the risk of deadlock, it can lead to inefficient use of resources because processes might hold resources they don't use immediately, increasing resource waiting times for other processes.

- **No Preemption**: One way to prevent deadlocks is to allow resources to be **forcibly taken away** from processes that are holding them. If a process cannot acquire all the resources it needs, it must release the ones it holds and try again later. For example, in some operating systems, memory pages or CPU cycles can be preempted and reassigned to higher-priority processes.
- **Circular Wait**: To prevent circular dependencies, impose a **global ordering** of resource acquisition. Processes are required to request resources in a **predefined order**. For example, if a system enforces that processes must always request Resource A before Resource B, and so on, circular waits can be avoided. This ensures that the system cannot fall into a cycle of processes waiting on each other.

2. **Deadlock Avoidance:**
    - Deadlock avoidance requires the system to make careful resource allocation decisions, ensuring that it never enters an unsafe state where deadlock could occur. A common approach is to use **Banker's Algorithm**.

Banker's Algorithm

Deadlock avoidance is a more **dynamic approach** that aims to ensure the system never enters an unsafe state where deadlock could occur. Unlike prevention, where processes are constrained by fixed rules, avoidance involves making real-time decisions about whether to allocate resources based on the current state of the system and potential future resource requests.

- One of the most well-known deadlock avoidance strategies is the **Banker's Algorithm**, developed by **Edsger Dijkstra**. This algorithm works by simulating resource requests in advance and determining if the system will remain in a **safe state** after the allocation.

Example: Consider a bank with a limited amount of available funds and several clients with loan requests. The Banker's Algorithm ensures that the bank only grants loan requests if doing so still allows the bank to meet the needs of all other clients. If granting the loan would leave the bank in a position where it couldn't meet future demands, the request is refused, keeping the system in a safe state.

- A **safe state** is one where the system can guarantee that all processes can complete their execution without causing a deadlock. If a resource allocation request leads to an **unsafe state** (where future resource requests could potentially cause a deadlock), the request is denied.

Example of the Banker's Algorithm:

- Assume a system has 12 units of resource R and three processes P1, P2, and P3.
  - **P1**: Maximum needs = 10 units, Currently holds = 5 units
  - **P2**: Maximum needs = 4 units, Currently holds = 2 units
  - **P3**: Maximum needs = 9 units, Currently holds = 2 units

- If **P1** requests 2 more units, the Banker's Algorithm simulates the allocation. It checks if, after granting the request, the system will still be able to satisfy the maximum demands of all processes. If not, the request is denied to avoid deadlock.

3. **Deadlock Detection and Recovery:**

   - While prevention and avoidance are proactive approaches, **deadlock detection** allows the system to identify a deadlock once it has occurred and then take **corrective actions** to recover.

Deadlock Detection:

   - In some systems, it may be more practical to allow deadlocks to occur occasionally, then detect and resolve them. A common technique is to use **wait-for graphs** or other detection algorithms that periodically check for cycles in the system's resource allocation. If a cycle is detected, the system recognizes that a deadlock has occurred.

Recovery from Deadlock:

Once a deadlock is detected, the system must take action to resolve it. The most common strategies for deadlock recovery include:

- **Process Termination**: The simplest solution is to **terminate one or more processes** involved in the deadlock to break the cycle of dependency.

  The system may choose to terminate the process that is least costly to restart, or it could terminate processes based on priority.

- **Resource Preemption**: In some cases, the system may forcibly **preempt resources** from one or more processes involved in the deadlock. The preempted resources are then reassigned to other processes to allow them to complete their execution and resolve the deadlock.

Choosing the Right Approach

The choice between **deadlock prevention**, **avoidance**, and **detection** depends on the specific requirements of the system. For instance:

- Systems where **reliability and uptime** are critical (e.g., **databases** or **real-time systems**) often use **prevention** or **avoidance** to ensure that deadlocks do not disrupt operations.
- In other environments, such as **batch processing systems**, **deadlock detection** and **recovery** might be more practical, since performance can be prioritized over constant monitoring.

Understanding and implementing the appropriate deadlock strategy is essential for ensuring **system stability** and **efficiency**, particularly in environments with **high resource contention**.

The Ostrich Algorithm

An alternative strategy, though not recommended in critical systems, is the **Ostrich Algorithm**. This approach essentially ignores deadlocks, under the assumption that they are rare and that the cost of prevention or detection is higher than the potential impact of the deadlock itself. This strategy is suitable only for systems where deadlocks are rare and non-critical.

Deadlocks represent a significant challenge in concurrent systems, where processes often compete for shared resources. If not managed properly, deadlocks can halt system operations indefinitely, causing downtime and wasting resources. Through techniques such as deadlock prevention, avoidance (e.g., Banker's Algorithm), and detection with recovery, systems can mitigate the risk of deadlocks and maintain smooth operation. Understanding and implementing deadlock management strategies is crucial for building reliable, efficient multi-threaded and multi-process systems.

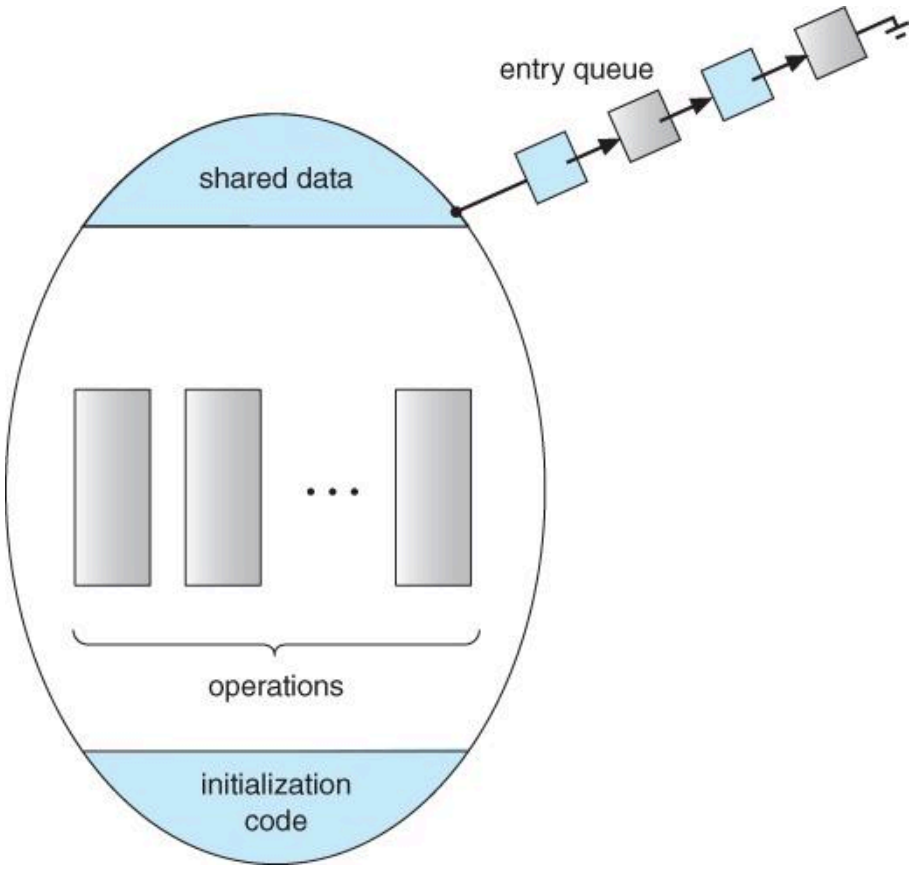
SYNCHRONIZATION MECHANISMS

In modern computing systems, **concurrency** is a common feature, as multiple processes or threads often run in parallel. This is particularly important in multi-core processors or distributed systems, where the ability to handle several tasks simultaneously is critical for performance and efficiency. However, running tasks concurrently introduces a new set of challenges—specifically, ensuring that processes or threads can operate **safely** and **efficiently** while sharing resources such as memory, files, or hardware.

Synchronization mechanisms are crucial in managing these challenges. Their role is to **coordinate the actions** of different processes or threads, ensuring that shared resources are accessed in a controlled manner. Without proper synchronization, the system can encounter serious issues such as:

- **Race conditions:** These occur when the outcome of a process depends on the **timing of access** to shared resources, leading to unpredictable and often incorrect results. Race conditions are particularly dangerous because they are often difficult to detect and reproduce.
- **Deadlocks:** A deadlock arises when two or more processes are **permanently blocked**, each waiting for the other to release a resource. In such cases, none of the processes can proceed, and the system may come to a halt.

The primary goal of synchronization is to **control access to critical sections** of code—these are the segments where shared resources are used. Synchronization mechanisms ensure that **only one process or thread** can enter a critical section at a time. This prevents **data corruption**, **inconsistent results**, and **system crashes**, as it eliminates the possibility of two processes making simultaneous, conflicting modifications to the same resource.



Beyond basic mutual exclusion, synchronization mechanisms also handle more complex scenarios such as:

- **Coordinating tasks**: In systems where tasks must be performed in a specific order, synchronization ensures that processes do not execute until certain conditions are met. For example, a **producer-consumer** system uses synchronization to ensure that the producer does not overwhelm the consumer with too much data, and the consumer does not attempt to retrieve data that has not yet been produced.
- **Managing resource availability**: Systems may have limited resources, such as a fixed number of database connections or hardware devices. Synchronization mechanisms, such as **semaphores**, are used to manage access to these resources, ensuring that only a limited number of processes can use them at any given time.

Effective synchronization is critical for the **stability and performance** of modern operating systems. Without it, shared resources would become sources of contention, and concurrent tasks could cause data inconsistencies or lead to system crashes. In fact, synchronization failures are some of the most difficult bugs to trace and resolve in software development, as concurrency issues often occur in **non-deterministic** ways.

For example, consider two threads trying to modify a shared variable representing a bank account balance. Without synchronization, both threads could read the balance at the same time and attempt to update it, leading to incorrect values being stored in memory. By using a synchronization tool like a mutex (mutual exclusion), the system can ensure that only one thread updates the balance at a time, maintaining data integrity.

To manage these challenges, **operating systems** offer a variety of synchronization tools designed for different concurrency scenarios. These tools range from simple mechanisms like **mutexes**, which ensure that only one thread accesses a resource at a time, to more advanced tools like **condition variables** and **monitors**, which allow for finer control over task coordination and resource access. In distributed systems, synchronization can become even more complex, requiring techniques such as **message passing** or **distributed locking** to coordinate processes across multiple machines.

Below, we begin by exploring one of the most fundamental and widely used synchronization mechanisms: **mutexes**, which play a key role in ensuring mutual exclusion in concurrent environments.

Example:

Consider a multi-threaded **banking application** where two threads, **Thread A** and **Thread B**, both attempt to **modify the balance** of the same bank account simultaneously.

- **Thread A** wants to **deposit** $500 into the account, while **Thread B** wants to **withdraw** $300.

- Without proper synchronization, both threads could **access and modify the account balance** at the same time. For example, the balance might initially be $1,000, but due to concurrent access, one thread could read the balance before the other updates it, leading to inconsistent or incorrect results.

To prevent this, a **mutex** (mutual exclusion lock) is used:

- **Thread A** first acquires the **mutex**, ensuring that no other thread can access the account balance while it is making the deposit.
- After **Thread A** finishes updating the balance to $1,500, it **releases the mutex**, allowing **Thread B** to acquire the lock and perform the withdrawal.
- **Thread B** then reduces the balance to $1,200 in a safe, synchronized manner.

By using the mutex, the system ensures that only one thread can modify the balance at any given time, preventing **race conditions** and ensuring that the final balance is correct.

Operating systems provide several synchronization mechanisms, each suited for different types of concurrency control. Below, we explore **mutexes**, one of the most fundamental tools for achieving mutual exclusion.

1. **Mutexes (Mutual Exclusion)**

What are Mutexes?

A **mutex** (short for **mutual exclusion**) is a simple but powerful synchronization mechanism designed to ensure that **only one process or thread** can access a **critical section** or shared resource at a given time. The mutex functions like a **lock**:

- A process **locks** the mutex when it enters the critical section, preventing other processes from accessing the resource.
- When the process finishes, it **unlocks** the mutex, allowing another waiting process to lock the mutex and access the resource.

By enforcing exclusive access, mutexes help prevent **race conditions** where two processes might try to read or modify a shared variable simultaneously, resulting in unpredictable or incorrect outcomes.

How Mutexes Work?

Mutexes follow a straightforward **lock-and-unlock** procedure:

1. **Lock the mutex**: When a process or thread needs to enter the critical section, it attempts to lock the mutex. If no other process is holding the lock, the mutex is acquired, and the process can safely access the shared resource.
2. **Critical section**: Once the mutex is locked, the process executes the code in the critical section without interference from other processes.
3. **Unlock the mutex**: After the process completes its operation, it releases the mutex, signaling that other processes waiting for the resource can now acquire it.

If a process attempts to lock a mutex that is already held by another process, it will **block** until the mutex becomes available, ensuring that only one process has access at a time.

Example of Using a Mutex:

```
pthread_mutex_t lock = PTHREAD_MUTEX_INITIALIZER;

void increment() {

    pthread_mutex_lock(&lock);  // Lock the mutex

    counter++;                  // Critical section

    pthread_mutex_unlock(&lock); // Unlock the mutex

}
```

In this example, the `lock` mutex ensures that only one process can modify the `counter` variable at a time, preventing race conditions.

Example: **Banking application**

Imagine a **banking application** where two processes, **Process A** and **Process B**, are both trying to modify the balance of the same account:

- **Process A** locks the mutex, preventing **Process B** from accessing the account balance while it is updating it.
- **Process A** updates the balance, and once done, it **unlocks** the mutex, allowing **Process B** to lock the mutex and make its updates.

Without a mutex, both processes might attempt to modify the balance at the same time, leading to inconsistencies in the final balance (e.g., lost updates).

Benefits of Mutexes:

- **Simplicity**: Mutexes are straightforward and easy to implement, making them an ideal choice for controlling access to shared resources.
- **Efficiency**: By only locking the critical section, mutexes minimize the time a process holds onto the resource, ensuring that other processes are not unnecessarily delayed.
- **Prevention of race conditions**: By ensuring mutual exclusion, mutexes eliminate race conditions that occur when processes or threads try to modify shared data concurrently.

Challenges with Mutexes:

While mutexes are effective, they introduce certain challenges:

- **Deadlock risk**: If two or more processes hold different mutexes while waiting for each other to release their locks, a **deadlock** can occur, freezing all processes involved.
- **Priority Inversion**: In real-time systems, a low-priority process holding a mutex may block a higher-priority process from progressing, leading to **priority inversion**. Some systems use protocols like **priority inheritance** to address this issue.
- **Busy Waiting**: If the process continuously checks for the mutex availability (instead of sleeping), it can lead to inefficient CPU usage—a problem known as **busy waiting**.

Advantages and Limitations:

- **Advantage**: Mutexes are efficient for mutual exclusion, ensuring that only one process accesses the critical section at a time.
- **Limitation**: If mutexes are not properly managed (e.g., a locked mutex is not released), deadlocks can occur.

2. Semaphores

What Are Semaphores?

A **semaphore** is a powerful synchronization mechanism used to control access to **shared resources** in a concurrent system. Semaphores manage the allocation of limited resources among multiple processes or threads by maintaining a **counter** that reflects the number of available resources.

How Semaphores Work?

The semaphore maintains a counter and provides two main operations:

- **P (Wait)**: When a process calls the P operation, the semaphore's counter is **decremented**. If the counter is **greater than 0**, it indicates that a resource is available, and the process can continue execution. However, if the counter reaches **0 or below**, it means that no resources are available, and the process is **blocked** until another process releases a resource.

- **V (Signal)**: When a process finishes using a resource, it calls the V operation, which **increments** the semaphore's counter. This indicates that a resource has been released and may allow a blocked process to continue.

Semaphores are particularly useful in systems where multiple processes need to access a shared resource, such as memory, files, or hardware devices, but access must be **controlled** to prevent conflicts or overuse.

Types of Semaphores:

1. **Binary Semaphore**:

A **binary semaphore** is a simpler version of a semaphore that functions similarly to a **mutex**. It has a value of either **0** or **1**:

- **1**: Indicates that the resource is **available** (unlocked).
- **0**: Indicates that the resource is **unavailable** (locked).

Binary semaphores are typically used for **mutual exclusion** (ensuring that only one process or thread can access a critical section at a time).

Example: Consider a situation where two threads need to access a **shared printer**. A binary semaphore can be used to lock the printer when one thread is using it and unlock it when the job is finished, ensuring that the printer is only accessed by one thread at a time.

2. **Counting Semaphore**:

A **counting semaphore** maintains a **counter** that allows multiple processes to access a resource simultaneously, as long as the number of active processes does not exceed the **maximum count**. When a process requests access, the counter is decremented, and when it finishes using the resource, the counter is incremented.

Use case: Counting semaphores are particularly useful for managing **limited resources**. For example, a database connection pool with a maximum of 10 connections can be controlled with a counting semaphore initialized to 10. Each time a process requests a connection, the semaphore is decremented. When the counter reaches zero, no additional processes can access the resource until a connection is released.

Example: In a **web server**, a counting semaphore can be used to manage simultaneous connections to a limited pool of database connections. As connections become available, the semaphore allows waiting processes to proceed.

Example of Binary Semaphore:

```
sem_t mutex;
sem_init(&mutex, 0, 1);
void critical_section() {
    sem_wait(&mutex);   // Enter the critical section
    // Access the shared resource
    sem_post(&mutex);   // Exit the critical section
}
```

In this example, the `mutex` semaphore allows only one process to access the critical section at a time.

Deadlocks with Semaphores:

While semaphores are valuable for synchronizing access to shared resources, they can also lead to **deadlocks** if not implemented carefully. Deadlocks occur when two or more processes are blocked, each waiting for the other to release a resource, creating a **cycle of dependency**. In the context of semaphores, this can happen if processes acquire semaphores in different orders.

Example of Deadlock with Semaphores:

Imagine two processes, **P1** and **P2**, and two semaphores, **S1** and **S2**, both initialized to 1 (binary semaphores):

1. **P1** locks **S1** and needs **S2** to continue.
2. **P2** locks **S2** and needs **S1** to proceed.
3. **P1** is now blocked, waiting for **S2**, and **P2** is blocked, waiting for **S1**.

Since neither process can proceed until the other releases the semaphore it holds, the system is now in a **deadlock**. Both processes are waiting indefinitely, and without intervention, this deadlock will not be resolved.

Preventing Deadlocks with Semaphores:

To avoid deadlocks with semaphores, several strategies can be applied:

- **Resource Ordering**: Ensure that all processes request semaphores in a **predefined order**. For example, always request **S1** before **S2**, so that processes do not create circular dependencies.
- **Timeouts**: Implement timeouts when waiting for a semaphore. If a process cannot acquire the semaphore within a certain period, it releases any resources it holds and retries later. This prevents processes from being stuck indefinitely.
- **Deadlock Detection**: Periodically check for cycles in the resource allocation and take corrective action if a deadlock is detected, such as forcibly releasing semaphores held by certain processes.

Advantages of Semaphores:

- **Flexibility**: Semaphores can be used for both **mutual exclusion** and **resource management**.
- **Suitability for Multi-Process Environments**: Semaphores are effective in multi-process or multi-threaded environments where resource contention needs to be carefully controlled.
- **Control Over Multiple Resources**: Counting semaphores allow for managing multiple instances of a resource, making them ideal for situations where a resource can be shared up to a limit.

Challenges of Semaphores:

- **Potential for Deadlocks**: If not carefully managed, semaphores can lead to deadlocks, as illustrated in the example above.
- **Priority Inversion**: When a lower-priority process holds a semaphore, a higher-priority process might be forced to wait, leading to inefficiencies (a problem known as **priority inversion**).
- **Complexity in Large Systems**: In complex systems with many resources and processes, managing semaphores can become error-prone, leading to issues like race conditions or deadlocks.

Semaphores are a versatile and widely-used synchronization mechanism for controlling access to limited resources. They help prevent conflicts in multi-process systems by ensuring that resources are not over-allocated. However, they must be used carefully to avoid deadlocks and ensure system efficiency. Understanding how semaphores work and how to implement them correctly is essential for managing concurrency in modern operating systems.

3. Monitors

What Are Monitors?

A **monitor** is a high-level synchronization construct that combines **mutual exclusion** with the ability to coordinate processes or threads through **condition variables**. Monitors ensure that only one process or thread can execute code within the monitor at any given time, providing a controlled environment for accessing shared resources.

Unlike lower-level synchronization mechanisms such as **mutexes** or **semaphores**, monitors are typically built into **high-level programming languages** like **Java** or **C#**, offering a more structured and user-friendly way to manage concurrency. This makes it easier for developers to avoid common synchronization errors like **race conditions** or **deadlocks**.

Key Features of Monitors:

- **Mutual Exclusion**: Monitors guarantee that only one process or thread can be active in the monitor at any time. This mutual exclusion prevents simultaneous access to shared resources, avoiding race conditions.
- **Condition Variables**: Monitors provide **condition variables** to allow processes or threads to **wait** until certain conditions are met. This capability is useful when a process needs to wait for a resource to become available or for a specific event to occur before proceeding.

Monitors are often considered a safer and higher-level alternative to mutexes and semaphores because they **encapsulate synchronization** within specific code blocks or methods, reducing the risk of errors associated with manual lock management.

How Does a Monitor Work?

Monitors work by using **synchronized methods** and **condition variables** to manage access to critical sections of code and coordinate process execution.

1. **Synchronized Methods:**

When a method in a monitor is declared as **synchronized**, it means that only one process or thread can **execute the method at a time**. If a process is executing a synchronized method, other processes that attempt to execute the same method are **blocked** until the first process finishes.

Example: In a multi-threaded banking system, a monitor could be used to synchronize access to account balances. A synchronized method ensures that only one thread can modify a user's balance at a time, preventing inconsistencies.

How it works:

- When a process enters a monitor (by calling a synchronized method), it automatically **locks** the monitor.
- The process executes the method, and other processes trying to access synchronized code are **queued**.
- Once the process completes, the **lock is released**, and one of the waiting processes is allowed to enter the monitor.

2. Condition Variables:

In addition to synchronized methods, monitors provide **condition variables** to allow processes to **wait for specific conditions** before continuing. These condition variables help coordinate complex interactions between processes.

- **Wait**: If a process cannot continue because a required condition is not met (e.g., waiting for a resource to become available), it can **wait** on a condition variable. This releases the monitor's lock, allowing other processes to execute in the meantime.
- **Signal**: Once the condition is met (e.g., another process frees the needed resource), a **signal** is sent to wake up the waiting process, which then reacquires the monitor's lock and resumes execution.

Example: Consider a **producer-consumer problem**, where one process (the producer) generates data and another (the consumer) processes it. The consumer might wait on a condition variable until the producer has added data to a shared buffer. Once data is available, the producer signals the consumer to wake up and process the data.

Example in Java:

```
public class SharedResource {
    private int counter = 0;
    public synchronized void increment() {
        counter++;  // Only one thread can access this method at a time
    }
}
```

In this example, the `increment()` method is synchronized, ensuring that only one thread can modify the `counter` at a time.

Another example of a Monitor in Java:

```
class SharedResource {
    private int count = 0;
    private final int limit = 10;

    // Synchronized method to ensure mutual exclusion
    public synchronized void produce() throws InterruptedException {
        while (count == limit)
{
            // Wait if the buffer is full
            wait();
        }
        count++;
        System.out.println("Produced: " + count);
        // Notify waiting consumers
        notify();
    }
    public synchronized void consume() throws InterruptedException {
        while (count == 0) {
            // Wait if the buffer is empty
            wait();
        }
        System.out.println("Consumed: " + count);
        count--;
        // Notify waiting producers
        notify();
    }
}
```

In this **Java monitor** example:

- The `produce()` and `consume()` methods are synchronized, ensuring only one thread can access the methods at a time.
- **Condition variables** are implicitly used through the `wait()` and `notify()` methods. When the producer tries to add an item to the buffer and the buffer is full, it waits. The

consumer notifies the producer when it consumes an item, allowing the producer to resume.

Advantages of Monitors:

- **Automatic Mutual Exclusion**: By encapsulating synchronization within the monitor, the programmer doesn't need to manually manage locks, reducing the risk of errors.
- **Ease of Use**: High-level language support for monitors simplifies complex synchronization patterns.
- **Thread Safety**: Monitors provide built-in mechanisms for ensuring that shared resources are accessed safely by multiple threads.

Challenges with Monitors:

- **Deadlocks**: Although monitors handle synchronization automatically, they are not immune to **deadlocks**. For example, if two processes wait on condition variables within separate monitors and depend on each other to signal, a deadlock can occur.
- **Limited Flexibility**: Monitors offer less flexibility compared to lower-level synchronization primitives like semaphores, particularly when dealing with more advanced concurrency control scenarios, such as managing multiple shared resources.
- **Overhead**: Because monitors often involve thread queuing and context switching, they may introduce performance overhead in highly parallel environments with frequent lock contention.

Monitors provide a **high-level, language-integrated** solution for synchronization, making them easier to use and less error-prone than low-level mechanisms like mutexes and semaphores. By encapsulating mutual exclusion and condition handling within methods, they help developers manage concurrent processes safely and effectively. However, as with any synchronization tool, careful design is needed to avoid deadlocks and ensure system performance remains efficient.

4. Atomic Operations

What Are Atomic Operations?

Atomic operations are fundamental synchronization mechanisms that ensure a given operation is performed **indivisibly**—meaning the operation is executed in its entirety without being interrupted or interfered with by other processes or threads. Atomic operations are essential in concurrent programming because they ensure that **shared resources** can be safely modified, even when multiple threads or processes are running in parallel. If an atomic operation starts, it will **complete entirely** before any other process or thread can observe or

interact with the intermediate state, which guarantees data integrity and avoids **race conditions**.

Key Characteristics of Atomic Operations:

- **Indivisibility**: The operation is either fully executed or not executed at all—there is no intermediate state visible to other threads or processes.
- **No Interruption**: During an atomic operation, no other processes or threads can interrupt or access the shared resource being modified.
- **Efficiency**: Atomic operations are often supported at the hardware level, making them fast and efficient compared to more complex synchronization mechanisms like locks.

Atomic operations are especially important in **low-level synchronization** where you need to perform simple operations like incrementing a counter, checking a flag, or swapping values without the overhead of locking mechanisms like **mutexes**.

Test & Set:

A classic example of an atomic operation is **Test & Set**, which combines checking a condition and modifying a variable into a single indivisible operation.

Example: Test-and-Set Operation

A classic example of an atomic operation is **Test-and-Set**, which is commonly used in synchronization to implement **locks**. The **Test-and-Set** operation performs two actions in a single, indivisible step:

1. **Test**: It checks the value of a memory location (e.g., a lock variable).
2. **Set**: If the value is available (e.g., the lock is free), it sets the value (locks the variable) in the same atomic step.

The key benefit of **Test-and-Set** is that both checking and modifying the variable happen **atomically**, meaning that no other process can intervene between the test and the set action. This ensures that if two threads attempt to acquire a lock using Test-and-Set simultaneously, only one of them will succeed, and the other will have to wait.

Example of Test & Set:

```
bool test_and_set(bool *lock) {

    bool old_value = *lock;
```

```
    *lock = true;

    return old_value;

}
```

This function checks the value of `lock` and sets it to `true` in a single atomic operation. If two processes try to set `lock` at the same time, only one will succeed, thus preventing race conditions.

How Test-and-Set Works:

- Suppose we have a shared variable (lock) that is initially set to 0 (unlocked).
- **Thread A** wants to enter a critical section and calls Test-and-Set:
    - The operation checks the value of the lock (0) and, if it is unlocked, sets it to 1 (locked) in a single atomic step. Thread A now holds the lock.
- **Thread B** tries to acquire the lock at the same time:
    - Test-and-Set checks the value of the lock and sees that it has already been set to 1 by Thread A. Thread B cannot acquire the lock and must wait.

This ensures that only one thread at a time can successfully acquire the lock, preventing concurrent access to the critical section.

Advantages of Atomic Operations:

- **Efficiency**: Atomic operations are often **hardware-supported**, making them much faster than higher-level synchronization tools like locks or semaphores. For simple operations like incrementing counters or flags, atomic operations are the most efficient choice.
- **Simplicity**: Atomic operations are simple to use and don't require the overhead of managing separate synchronization mechanisms (e.g., mutexes). This makes them ideal for low-level tasks where performance is critical.
- **Prevent Race Conditions**: Since atomic operations ensure that a shared resource is **fully modified** before another process can interact with it, they help prevent **race conditions**. For example, if multiple threads try to increment a shared counter, an atomic operation will ensure that each increment is completed fully before the next one starts, avoiding corrupted results.

Atomic Operations:

1. Atomic Increment:

One of the simplest examples of an atomic operation is **atomic increment**. In multi-threaded systems, multiple threads may try to increment a shared variable, such as a counter. Without atomicity, two threads could read the same value of the counter, increment it, and store the same result, effectively losing one of the increments. With atomic increment, the entire read-modify-write sequence happens indivisibly, ensuring that no increments are lost.

Example in C:

```
atomic_increment(&counter);
```

In this case, the `atomic_increment()` operation ensures that no other thread can read or modify the value of `counter` until the increment operation is complete.

2. Compare-and-Swap (CAS):

Another commonly used atomic operation is **Compare-and-Swap (CAS)**, which is crucial for implementing **lock-free data structures**. The CAS operation compares the value at a memory location to an expected value, and if they match, it swaps the value with a new one. This all happens atomically, making CAS a powerful tool for ensuring consistency in multi-threaded systems.

- **How it works**:
  - CAS takes three arguments: the memory location, the expected value, and the new value.
  - If the current value at the memory location matches the expected value, CAS updates the memory location to the new value atomically.
  - If the value does not match, the operation fails, and the process can retry.

Example in C:

```
int old_value = atomic_compare_and_swap(&var, expected, new_value);
```

In this case, if the value of `var` equals `expected`, it will be replaced with `new_value` in one atomic step.

Challenges with Atomic Operations:

- **Limited Scope**: While atomic operations are highly efficient, they are usually limited to **simple operations** (like incrementing, setting, or swapping values). For more complex

synchronization requirements, higher-level mechanisms like locks or semaphores are needed.

- **Hardware Dependency**: Not all systems provide robust support for atomic operations, especially older hardware architectures. The efficiency and availability of atomic operations often depend on the underlying hardware.
- **Potential for Deadlocks**: Although atomic operations prevent race conditions, improper usage, such as combining multiple atomic operations without careful coordination, can lead to **deadlocks** or **livelocks**, where processes are stuck waiting for resources or endlessly retrying.

Atomic operations are a fundamental building block in concurrent programming, ensuring that shared resources are modified safely and efficiently in a multi-threaded environment. By making small, crucial operations indivisible, atomic operations prevent race conditions and provide a fast alternative to more complex synchronization mechanisms like locks or semaphores. However, developers must understand their limitations and be cautious when designing systems that require more sophisticated synchronization.

5. Condition Variables

What Are Condition Variables?

Condition variables are synchronization mechanisms that work alongside **mutexes** to manage more complex coordination between threads. They allow threads to **wait** for specific conditions to become true before continuing execution. Unlike busy waiting, where a thread repeatedly checks whether a condition has been met, condition variables allow threads to **block** efficiently, freeing up CPU resources, until they are notified that the condition has changed.

By combining **condition variables** with **mutexes**, threads can safely coordinate access to shared resources without causing performance bottlenecks or race conditions. Condition variables are typically used in situations where a thread must wait for another thread to make progress or change a shared state (e.g., adding data to a buffer, releasing a lock).

How Do They Work?

Condition variables operate in tandem with **mutexes** to manage the coordination between waiting and signaling threads.

1. **Waiting on a Condition**:
    - When a thread needs to wait for a certain condition to become true, it first acquires a **mutex** to ensure safe access to the shared resource.

- The thread then calls the `wait()` function on the condition variable, which releases the mutex and **blocks** the thread until the condition is met. Releasing the mutex allows other threads to access the shared resource while the original thread is waiting.
- The thread remains blocked and doesn't consume CPU resources, making this approach highly efficient.

2. **Signaling the Condition**:
   - Another thread, which changes the shared condition (e.g., adding data to a buffer or releasing a resource), can **signal** the condition variable by calling the `signal()` or `broadcast()` function.
   - `signal()` wakes up **one** waiting thread, while `broadcast()` wakes up **all** waiting threads.
   - When the waiting thread is unblocked, it reacquires the mutex and continues its execution. This guarantees that the shared resource is only accessed in a controlled manner, preventing race conditions.

Example of Condition Variable in C (POSIX):

```
pthread_cond_t cond = PTHREAD_COND_INITIALIZER;
pthread_mutex_t mutex = PTHREAD_MUTEX_INITIALIZER;
void wait_for_condition() {
    pthread_mutex_lock(&mutex);     // Lock the mutex
    pthread_cond_wait(&cond, &mutex); // Wait for the condition
    // Once awakened, continue execution
    pthread_mutex_unlock(&mutex);   // Unlock the mutex
}
void signal_condition() {
    pthread_mutex_lock(&mutex);
    pthread_cond_signal(&cond);      // Signal to unblock one thread
    pthread_mutex_unlock(&mutex);
}
```

In this example, one thread waits for a condition to become true, while another signals that the condition has changed, unblocking the waiting thread.

Another Example of Condition Variables in Use:

A common use case for condition variables is in the **producer-consumer problem**, where one thread (the producer) generates data, and another thread (the consumer) processes the data.

- **Producer**: The producer thread adds items to a shared buffer.
- **Consumer**: The consumer thread removes items from the buffer and processes them.

The consumer should only proceed when the buffer has data. If the buffer is empty, the consumer must wait until the producer adds more data. Condition variables can help the consumer wait efficiently for the producer to signal that the buffer is no longer empty.

Example in C++:

```
#include <iostream>
#include <queue>
#include <mutex>
#include <condition_variable>
#include <thread>
std::queue<int> buffer;
const int BUFFER_SIZE = 10;
std::mutex mtx;
std::condition_variable cond_var;
void producer() {
    int item = 0;
    while (true) {
        std::unique_lock<std::mutex> lock(mtx);
        // Wait until there is space in the buffer
        cond_var.wait(lock, [] { return buffer.size() < BUFFER_SIZE; });
        buffer.push(++item);
        std::cout << "Produced: " << item << std::endl;
        // Signal the consumer that new data is available
        cond_var.notify_one();
        lock.unlock();
        std::this_thread::sleep_for(std::chrono::milliseconds(100));
    }
}
void consumer() {
    while (true) {
        std::unique_lock<std::mutex> lock(mtx);
```

```
        // Wait until there is data in the buffer
        cond_var.wait(lock, [] { return !buffer.empty(); });
        int item = buffer.front();
        buffer.pop();
        std::cout << "Consumed: " << item << std::endl;
        // Signal the producer that space is available in the buffer
        cond_var.notify_one();
        lock.unlock();
        std::this_thread::sleep_for(std::chrono::milliseconds(150));
    }
}
int main() {
    std::thread t1(producer);
    std::thread t2(consumer);
    t1.join();
    t2.join();
    return 0;
}
```

In this example:

- The **producer** adds items to the buffer and signals the consumer when new items are available.
- The **consumer** waits on the condition variable until the buffer has data. When the producer signals that data is available, the consumer resumes execution, processes the data, and notifies the producer that there is space available in the buffer.

Operations on Condition Variables

- `wait()`: This operation blocks a thread until the specified condition is met. While waiting, the thread releases the mutex, allowing other threads to access the shared resource.

Example: In the producer-consumer problem, the consumer calls `wait()` on the condition variable until the buffer contains items.

- `signal()`: This operation unblocks **one** waiting thread, allowing it to check the condition and continue execution if the condition has become true.

Example: When the producer adds an item to the buffer, it signals the consumer to wake up and consume the item.

- `broadcast()`: This operation unblocks **all** waiting threads. It is useful when multiple threads are waiting for the same condition and can all proceed once the condition becomes true.

Example: If multiple consumers are waiting for items to be added to a buffer, the producer can use `broadcast()` to wake them all up when new items are available.

Advantages of Condition Variables:

- **Efficient Waiting**: Condition variables allow threads to block without wasting CPU resources. The waiting thread only resumes execution when another thread signals that the condition has been met.
- **Coordination Between Threads**: Condition variables enable more complex synchronization patterns, where one thread depends on another to make progress (e.g., producers and consumers working together).
- **Avoiding Busy Waiting**: Without condition variables, a thread might repeatedly check if a condition is met (busy waiting), which wastes CPU cycles. Condition variables eliminate this inefficiency by allowing the thread to wait until the condition is signaled.

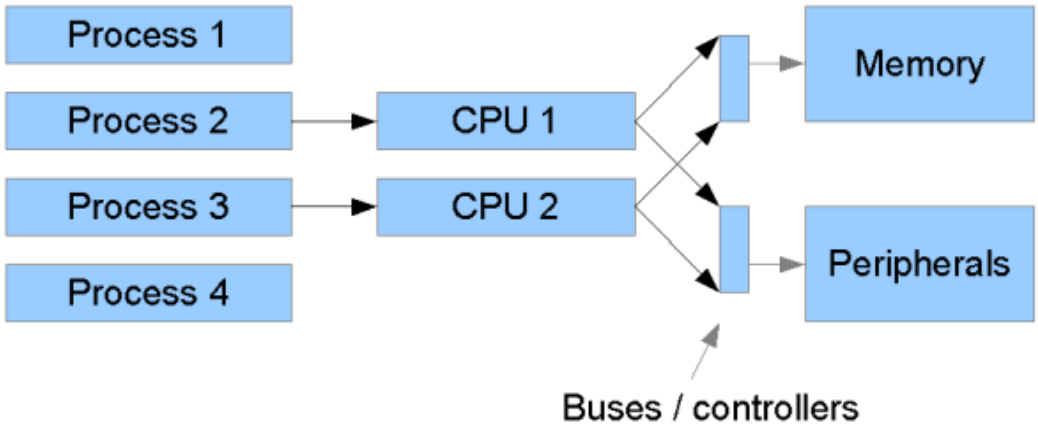
Challenges with Condition Variables:

- **Deadlock Risk**: Improper usage of condition variables can lead to **deadlocks**, where multiple threads are waiting for conditions that will never be signaled. This can occur if a thread signals the condition before another thread starts waiting, leaving the waiting thread blocked indefinitely.
- **Spurious Wakeups**: Sometimes, a thread can wake up even when the condition has not been signaled (known as a **spurious wakeup**). To avoid issues, condition variables should always be used with a **while loop** to repeatedly check the condition after waking up.
- **Overhead of Mutex Locking**: Since condition variables are always used with mutexes, there can be some performance overhead due to the repeated acquisition and release of locks, especially in highly concurrent systems.

Condition variables are essential for building more sophisticated synchronization mechanisms in concurrent systems.

By allowing threads to **wait efficiently** for specific conditions, they help improve resource management and coordination between processes or threads. However, developers need to use condition variables carefully to avoid issues like deadlocks and spurious wakeups, ensuring that conditions are always checked appropriately.

However, synchronization mechanisms are indispensable in managing the **complexity of concurrency** in multi-threaded environments. When used effectively, they provide the foundation for **system stability**, **resource efficiency**, and **reliable performance** in any application or operating system. By minimizing the risks of conflicts and inefficiencies, synchronization allows developers to build scalable, robust systems capable of handling the demands of modern computing.



Synchronization ensures that processes and threads coordinate their access to **shared resources** in a way that prevents conflicts and maintains **data integrity**. In this context, mechanisms like mutexes provide mutual exclusion, semaphores manage resource availability, and monitors help coordinate complex interactions.

In conclusion, c**oncurrency and synchronization** are closely intertwined in modern operating systems, as the ability to run multiple processes or threads simultaneously is only useful when **shared resources** can be accessed safely and efficiently. **Concurrency** enables systems to maximize performance and responsiveness by allowing multiple tasks to progress at the same time. However, without proper **synchronization mechanisms**, such as **mutexes**, **semaphores**, and **monitors**, concurrency can lead to **race conditions**, **deadlocks**, and other critical issues that undermine system stability.

Effective synchronization is essential for maintaining the benefits of concurrency while minimizing risks. By implementing the right synchronization tools, developers can harness the power of concurrency to build **reliable**, **efficient**, and **scalable systems**, ensuring smooth operation in **multi-threaded environments** and preventing common pitfalls like **data corruption** and **system crashes**.

Self-assessment questions:

1. What is process concurrency, and why is it important in modern operating systems?
2. What is a race condition, and how does it affect program execution?
3. Explain the four Coffman conditions that must be true for a deadlock to occur.
4. What is the difference between a binary semaphore and a counting semaphore?
5. How do mutexes ensure mutual exclusion? Provide an example of how a mutex is used to protect a critical section.
6. What is the Banker's Algorithm, and how does it help in avoiding deadlocks?
7. What are atomic operations, and why are they important in concurrent programming?
8. What is the purpose of condition variables, and how do they work in conjunction with mutexes?
9. Explain the difference between a mutex and a critical section in Windows.
10. In Linux, what is the function of `pthread_cond_wait()` and `pthread_cond_signal()`?
11. What is a deadlock, and how can it be detected and resolved in an operating system?
12. How do semaphores help in synchronizing access to shared resources in multi-threaded environments?
13. What is a monitor in concurrent programming, and how does it differ from mutexes or semaphores?
14. Explain the Test-and-Set operation and its role in achieving mutual exclusion.
15. What are the key differences between busy waiting and condition variables for thread synchronization?

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