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BCA Honours | Semester VI | BCA6CJ305

Principles of Operating System

Module 2 Comprehensive Notes

Module 2: Concurrency, Process Synchronization, and Deadlocks

Concurrent execution of multiple threads accessing shared data structures can trigger race conditions and inconsistent states. Synchronization primitives coordinate concurrent execution, while deadlock management guarantees progress.

2.1 The Critical Section Problem

A critical section is a code block accessing shared mutable memory. A valid synchronization solution must satisfy three criteria:

1. **Mutual Exclusion:** If process P_i is executing in its critical section, no other processes can execute in their critical sections simultaneously.
2. **Progress:** If no process is executing in its critical section and some processes wish to enter, only those processes not executing in their remainder sections can participate in deciding who enters next, and selection cannot be postponed indefinitely.
3. **Bounded Waiting:** There exists a bound on the number of times other processes are allowed to enter their critical sections after a process has requested entry before that request is granted, preventing starvation.

2.2 Classical Synchronization Primitives: Semaphores and Mutexes

A **Semaphore** S is a synchronized integer variable accessed strictly through two atomic operations: `wait()` (or P) and `signal()` (or V):

$$\begin{aligned} \text{wait}(S): \quad & \text{while } S \\ le0 \text{ do nothing;} \quad & S \leftarrow S - 1 \end{aligned}$$

$$\text{signal}(S): \quad S \leftarrow S + 1$$

- **Counting Semaphore:** Value ranges over an unrestricted domain, coordinating access to finite resource pools.
- **Binary Semaphore (Mutex):** Value restricted to 0 or 1, enforcing strict mutual exclusion.

2.3 Classical Concurrency Problems

- **Producer-Consumer (Bounded Buffer) Problem:** Producers insert items into a shared buffer of size N; consumers extract items. Synchronized using three semaphores: `mutex` (protecting buffer access), `empty` (tracking available slots, initialized to N), and `full` (tracking filled slots, initialized to 0).

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- **Dining Philosophers Problem:** Five philosophers sit around a table with five chopsticks, alternating between thinking and eating. Illustrates deadlock and starvation hazards when acquiring multiple shared resources.

2.4 Deadlock Theory and Characterization

A deadlock occurs when a set of concurrent processes are permanently blocked because each holds resources while waiting for resources held by others. Deadlock can arise if and only if all four **Coffman Conditions** hold simultaneously:

1. **Mutual Exclusion:** At least one resource is held in a non-shareable mode.
2. **Hold and Wait:** A process holds allocated resources while waiting to acquire additional resources held by other processes.
3. **No Preemption:** Resources cannot be forcibly confiscated; they are released only voluntarily by the holding process after completing its task.
4. **Circular Wait:** A closed chain of processes $\{P_0, P_1, \ldots, P_n\}$ exists such that P_0 waits for a resource held by P_1, P_1 waits for P_2, and P_n waits for P_0.

2.5 Deadlock Avoidance: The Banker's Algorithm

Edsger Dijkstra's Banker's Algorithm avoids deadlocks by dynamically evaluating resource allocations to ensure the system never enters an **Unsafe State** (a state from which deadlock could become inevitable). It tests whether there exists at least one **Safe Sequence** $\langle P_1, P_2, \ldots, P_n \rangle$ such that for each P_i, its maximum remaining resource demands can be satisfied by currently available resources plus resources held by all preceding processes P_j (j < i).

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1. Architectural Trade-offs and Computational Complexity

Software architects and systems engineers designing scalable computational pipelines centered on Principles of Operating System must methodically navigate core trade-offs:

- **Time Complexity Optimization versus Spatial Footprint:** In high-throughput algorithmic pipelines handling Module 2 Core Concepts and Methods, pre-computing intermediate lookup tables, spatial indices, and hashing structures achieves near-instantaneous $O(1)$ query latency, but inflates the physical memory footprint. Conversely, in-place algorithms minimize RAM utilization at the cost of higher CPU cycle counts. Modern architectures dynamically calibrate memory allocations using memory-mapped files and cache-aware structures.
- **Concurrency Scalability versus Thread Contention:** While multi-core hardware allows horizontal execution, concurrent modifications to shared state structures create severe lock contention, thread synchronization bottlenecks, and cache line invalidation storms. High-performance frameworks deploy lock-free algorithms, optimistic concurrency control, and atomic compare-and-swap (CAS) primitives.

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- **Algorithmic Determinism versus Heuristic Scalability:** Exact mathematical algorithms frequently encounter NP-hard combinatorial barriers as problem dimensions scale. Contemporary systems bridge this gap by deploying bounded approximation algorithms and meta-heuristics that produce near-optimal solutions within guaranteed execution time windows.

2. Empirical Comparative Framework

A structured comparative assessment clarifies operational distinctions across conventional paradigms and modern production implementations in Principles of Operating System:

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3. Production Implementation Patterns and Resilience Engineering

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