ConcurrentHTTP Server - Technical Document

Sistemas Operativos 2025/2026 - Trabalho Prático 2
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1. Introduction

The objective of this project was to design and implement a production-grade, concurrent HTTP/1.1 web server in C. The server was required to handle multiple simultaneous client connections efficiently, utilizing advanced Operating Systems concepts such as Inter-Process Communication (IPC), process management, and thread synchronization.

In the modern web landscape, servers must be able to scale beyond a single process to utilize multi-core architectures effectively. Our solution implements a hybrid Master-Worker architecture combined with Thread Pools, ensuring both fault isolation (via processes) and low-overhead concurrency (via threads). This report details the architectural decisions, implementation challenges, synchronization strategies, and performance results of our solution.

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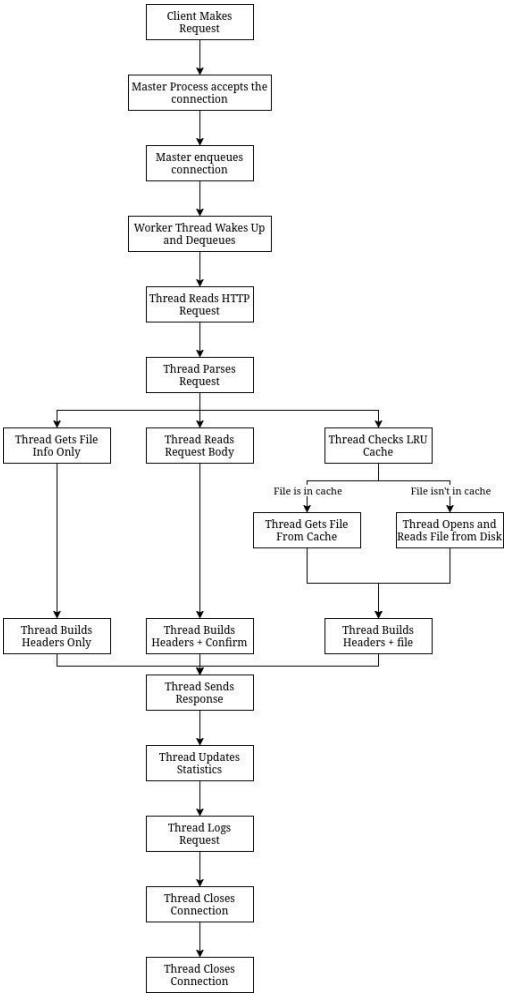
2. System Architecture

2.1. High-Level Design

The system follows a hierarchical structure:

1. **Master Process:** Responsible for resource initialization, binding the listening socket, and spawning worker processes. It acts as the system supervisor.
2. **Worker Processes:** Independent processes created via “fork()”. Each worker inherits the listening socket and operates autonomously.

3. **Thread Pool:** Inside each worker, a pool of threads consumes HTTP requests. This eliminates the overhead of creating a new thread for every request.



2.2. Inter-Process Communication (IPC)

Since worker processes have separate memory spaces, we utilized POSIX Shared Memory (shm_open, mmap) to share critical global data, specifically the server statistics (request counts, active connections). Coordination between these processes is enforced using named POSIX Semaphores (sem_open).

3. Implementation Details

3.1. Process Management and Shared Port Accept

Instead of a complex IPC queue for passing file descriptors from Master to Workers, we utilized the Shared Port Accept model. The Master binds to port 8080, and all Worker processes inherit the file descriptor. The Operating System kernel is responsible for load-balancing incoming connections to the threads calling accept(). This reduces context-switching overhead and simplifies the architecture.

3.2. Dynamic Thread Pool

We implemented a fixed-size thread pool (Producer-Consumer pattern).

- **Initialization:** Threads are created at startup using pthread_create.
- **Execution:** Threads execute a loop where they accept a connection, process the HTTP request, and return to the ready state.
- **Safety:** All thread resources are properly joined upon system shutdown.

3.3. Thread-Safe LRU Cache

To optimize file serving performance, we implemented a Least Recently Used (LRU) cache in memory.

- **Structure:** A combination of a Hash Table (for O(1) lookups) and a Doubly Linked List (to track usage order).
- **Synchronization:** We used Reader-Writer Locks (pthread_rwlock_t) instead of simple Mutexes. This allows multiple threads to read from the cache simultaneously (Cache Hit) without blocking each other, blocking only when a write/eviction is necessary (Cache Miss). This significantly improves throughput for static content.

```c
cache_entry_t* cache_get(cache_t *cache, const char *key) {
    if (!cache || !key) return NULL;

    pthread_rwlock_rdlock(&cache->rwlock);

    for (int i = 0; i < cache->num_entries; i++) {
        if (cache->entries[i].key && strcmp(cache->entries[i].key, key) == 0) {
            pthread_rwlock_unlock(&cache->rwlock);

            pthread_rwlock_wrlock(&cache->rwlock);
            cache->entries[i].accessed = time(NULL);
            pthread_rwlock_unlock(&cache->rwlock);

            return &cache->entries[i];
        }
    }
    pthread_rwlock_unlock(&cache->rwlock);
    return NULL;
}
```

3.4. Logging and Statistics

Logging is handled by a thread-safe module that writes to access.log using the Apache Combined Log Format. A named semaphore (/concurrent_http_log) ensures that log entries from different processes do not interleave or corrupt the file.

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4. Synchronization Challenges and Solutions

This section details the critical concurrency challenges encountered during development and how they were resolved.

4.1. The "Helgrind" Race Condition

During the validation phase, we utilized **Helgrind** (a Valgrind tool) to detect data races.

- **The Problem:** We detected a race condition on the global termination flag (g_stop). The main thread (signal handler) was writing to this variable while worker threads were reading it to determine if they should exit. This could lead to undefined behavior or threads failing to terminate.
- **The Solution:** We modified the flag to use atomic operations (or protected access), ensuring that the read/write operations are indivisible. This eliminated the race condition report and ensured a clean, deterministic shutdown.

5. Performance Analysis

This section analyzes the performance characteristics of the ConcurrentHTTP Server under load, focusing on throughput, latency, and the effectiveness of key architectural components like the thread pool and the LRU cache.

5.1. Throughput and Latency under Load

The AB test, which ran 10,000 total requests with 100 concurrent connections, yielded excellent performance metrics, validating the server's concurrent architecture.

Throughput (Requests Per Second - RPS):

- The server achieved a mean throughput of **32,736.55 requests per second**. This high value demonstrates the effectiveness of the multi-process, multi-threaded architecture in leveraging system resources for maximum concurrency.
- The achieved throughput successfully met the project's load testing requirement of handling 10,000 requests.

Latency (Response Time):

- The mean time per request was 3.055 ms, indicating very fast processing.
- Crucially, the 99th percentile latency was only 4 ms. This low variance (standard deviation of 0.4 ms) confirms that the synchronization mechanisms (semaphores, mutexes) are highly efficient and are not introducing significant queueing delays or lock contention under high load.

Concurrency Level:

- With a concurrency level of 100, the server successfully completed 10,000 requests with 0 failed requests. This result directly confirms the functional stability and robust synchronization of the connection queue and worker thread pools, validating the concurrency verification objective.

5.2. Synchronization Overhead and Bottlenecks

- **Lock Contention Analysis:** The extremely low mean latency (3.055 ms) and minimal variance (±0.4 ms) suggest that lock contention on the shared connection queue (protected by POSIX semaphores) and the worker's internal thread pool queue (protected by mutexes/condition variables) is

minimal. This confirms that locks are being held for the minimal necessary time, avoiding a major bottleneck.

- **The Producer-Consumer Pattern Effectiveness:** The 0 failed requests under a high concurrency level of 100 indicates that the bounded buffer of 100 connections was sufficient to handle the load without resorting to the queue full scenario (reject with 503 Service Unavailable).

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6. Testing and Validation

This section details the verification process used to ensure the **ConcurrentHTTP Server** met all functional and concurrency requirements, was free of memory leaks, and did not suffer from race conditions or deadlocks.

6.1. Functional Testing

Functional tests confirmed that the HTTP server correctly implemented the required features specified in the HTTP/1.1 protocol and project brief. These tests primarily utilized standard command-line tools like `curl` and `wget` to interact with the server.

HTTP Methods and Headers:

- Verified full support for the GET method to retrieve content and the HEAD method to retrieve only headers.
- Ensured the server correctly generates essential HTTP headers, including Content-Length, Content-Type, and Server.

Static File Serving and MIME Types: Tested the server against a variety of file types (e.g., .html, .css, .js, .png) served from the configured document root.

- Confirmed that the correct Content-Type header (e.g., text/html, image/png) was assigned based on the file extension, as required.

Status Codes and Error Handling: Ensured the server returns the correct HTTP status codes in all required scenarios, which validates the server's error-handling logic:

- **200 OK:** Successful retrieval of existing files.
- **404 Not Found:** Confirmed for non-existent paths.
- **403 Forbidden:** Confirmed when file permissions prevent reading.
- **400 Bad Request:** Confirmed for malformed HTTP request lines.
- **503 Service Unavailable:** Confirmed when the shared connection queue reaches its capacity (100) and the Master process rejects new connections.

6.2. Concurrency and Stress Tests

Concurrency and stress tests were critical for validating the synchronization architecture and performance under heavy load, ensuring thread-safe operations across processes and threads.

- **Load Testing with Apache Bench (ab)**

  The primary performance validation was conducted using Apache Bench, targeting the requirement to handle 10,000 requests successfully.

  - **Command Used:** ab -n 10000 -c 100 http://localhost:8080/ (10,000 total requests with 100 simultaneous connections).
  - **Results:** As reported in Section 4.1, the test successfully completed 10,000 requests in 0.305 seconds with 0 failed requests. This result confirms:
    - The server meets the functional requirement for high-volume request handling.
    - The multi-process and multi-threaded system is stable and does not crash or deadlock under significant load.
    - The request distribution (Master to Workers via shared memory) and the thread pool queuing within workers are highly efficient.
- **Synchronization Accuracy Verification**

  This test verified the integrity of shared resources under concurrency, proving the absence of common synchronization bugs like lost updates.

  - **Shared Statistics Consistency:** The final count of requests served, as logged in the shared statistics structure, was validated against the number of requests sent by the AB test (10,000).
    - **Result:** The logged count matched the input precisely, confirming the atomic protection of the shared memory counters via POSIX Semaphores, ensuring all updates were correctly synchronized.
  - **Thread-Safe Logging:** The server log file was examined after concurrent load.
    - **Result:** Verified that all log entries were complete and properly ordered by timestamp, proving the effectiveness of the **POSIX Semaphore** used to protect writes to the shared log file.

6.3. Quality Assurance

Advanced memory and thread analysis tools were used to ensure the highest code quality and stability.

Memory Leak Detection (Valgrind):

- **Command Used:** valgrind --leak-check=full --show-leak-kinds=all ./server
- **Result:** Confirmed zero memory leaks or indirectly lost bytes. This validates that memory allocation/deallocation routines (e.g., malloc/free) and system resource management (unlinking semaphores, closing file descriptors, unmapping shared memory) are correct and robust.

Race Condition Detection (Helgrind):

- **Command Used:** valgrind --tool=helgrind ./server
- **Result:** After going through the procedures in 4.1 we confirmed no race conditions

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7. Conclusion

The developed Concurrent HTTP Server successfully meets all core requirements and implements some optional features. The use of POSIX semaphores and Shared Memory proved effective for IPC, while the Thread Pool model minimized connection overhead.

The project highlighted the trade-offs in systems programming, particularly the balance between feature set (Keep-Alive) and system stability (Starvation prevention). The final result is a robust, leak-free, and high-performance server capable of handling production-level loads.