# Operating Systems & Linux Internals for HFT

**Complete Guide: Theory, Implementation, and Production Optimization**

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# Chapter 1: Process Management & Scheduling

### 1.1 Foundational Overview

### Layman's Intuition

Imagine a restaurant kitchen with one chef and multiple orders. The chef can't cook everything simultaneously—they must decide which dish to prepare first, switch between orders efficiently, and ensure no customer waits too long. The operating system's scheduler is like that chef, managing which programs (processes) get CPU time and when.

### Technical Foundation

**Process:** An instance of a program in execution, containing:

- **Code segment** (text): Executable instructions
- **Data segment**: Global/static variables
- **Stack**: Local variables, function calls
- **Heap**: Dynamic memory allocation
- **Process Control Block (PCB)**: Metadata (PID, state, registers, etc.)

**Process States:**

```
NEW → READY → RUNNING → TERMINATED
          ↑       ↓
          └── WAITING/BLOCKED
```

**State Transitions:**

- **NEW → READY:** Process created, awaiting CPU
- **READY → RUNNING:** Scheduler dispatches process
- **RUNNING → READY:** Time quantum expired (preemption)
- **RUNNING → WAITING:** I/O request, resource unavailable
- **WAITING → READY:** I/O completed, resource available
- **RUNNING → TERMINATED:** Process completes or killed

### Industry Importance

**In HFT Systems:**

- **Market data processing:** Real-time tick processing requires deterministic scheduling
- **Order execution:** Sub-microsecond latency demands predictable CPU allocation
- **Risk management:** Time-critical calculations need guaranteed CPU time

**In Backend Engineering:**

- **Request handling:** Efficient process/thread scheduling for concurrent requests
- **Batch processing:** Resource allocation for background jobs
- **Service reliability:** Process isolation prevents cascading failures

## 1.2 Core Concepts and Deep Dives

### Process Creation

#### Unix fork() System Call:

#### Mechanism:

1. Duplicate parent process
2. Create new PCB with unique PID
3. Copy parent's memory space (Copy-on-Write optimization)
4. Inherit file descriptors, signal handlers
5. Return: PID of child to parent, 0 to child

#### C Implementation:

```
#include &lt;unistd.h&gt;
#include &lt;stdio.h&gt;
#include &lt;sys/types.h&gt;

int main() {
    pid_t pid = fork();

    if (pid &lt; 0) {
        // Fork failed
        perror("fork failed");
        return 1;
    }
    else if (pid == 0) {
        // Child process
        printf("Child process: PID=%d, Parent PID=%d\n",
               getpid(), getppid());

        // Execute new program
        char *args[] = {"/bin/ls", "-l", NULL};
        execvp(args[0], args);

        // execvp only returns on error
        perror("execvp failed");
        return 1;
    }
    else {
        // Parent process
        printf("Parent process: PID=%d, Child PID=%d\n",
               getpid(), pid);

        // Wait for child to complete
        int status;
        waitpid(pid, &amp;status, 0);

        if (WIFEXITED(status)) {
            printf("Child exited with status %d\n",
                   WEXITSTATUS(status));
```

```
        }
    }

    return 0;
}
```

**Copy-on-Write (COW) Optimization:**

Instead of immediately copying entire memory space, kernel marks pages as read-only and shared. On write attempt:

1. Page fault triggered
2. Kernel copies page
3. Updates page table
4. Resumes execution

**Benefits:**

- Faster fork(): O(1) vs O(n) memory copy
- Memory efficient: Shared pages until modified
- Critical for HFT: Minimal latency impact

**C++ Demonstration:**

```
#include &lt;unistd.h&gt;
#include &lt;sys/wait.h&gt;
#include &lt;iostream&gt;
#include &lt;cstring&gt;

void demonstrate_cow() {
    const size_t SIZE = 1024 * 1024;  // 1MB
    char* data = new char[SIZE];
    memset(data, 'A', SIZE);

    std::cout &lt;&lt; "Before fork, data address: " &lt;&lt; (void*)data &lt;&lt; std::e

    pid_t pid = fork();

    if (pid == 0) {
        // Child process
        std::cout &lt;&lt; "Child: data address " &lt;&lt; (void*)data &lt;&lt; std::endl

        // This write triggers COW
        data[0] = 'B';

        std::cout &lt;&lt; "Child: after write, data[0]=" &lt;&lt; data[0] &lt;&lt; std::
        delete[] data;
        exit(0);
    } else {
        // Parent process
        sleep(1);  // Let child run first
```

```
        std::cout &lt;&lt; "Parent: data[0]=" &lt;&lt; data[0] &lt;&lt; std::endl;
        delete[] data;

        waitpid(pid, nullptr, 0);
    }
}
```

## CPU Scheduling Algorithms

### 1. First-Come First-Served (FCFS)

**Algorithm:** Process that arrives first gets CPU first (FIFO queue)

**Pros:**

- Simple implementation
- No starvation

**Cons:**

- **Convoy effect:** Short processes wait for long processes
- Poor average waiting time
- Not suitable for interactive systems

**Implementation:**

```
struct Process {
    int pid;
    int arrival_time;
    int burst_time;
    int waiting_time;
    int turnaround_time;
};

void fcfs_scheduling(std::vector&lt;Process&gt;&amp; processes) {
    // Sort by arrival time
    std::sort(processes.begin(), processes.end(),
              [](const Process&amp; a, const Process&amp; b) {
                  return a.arrival_time &lt; b.arrival_time;
              });

    int current_time = 0;

    for (auto&amp; p : processes) {
        if (current_time &lt; p.arrival_time) {
            current_time = p.arrival_time;
        }

        p.waiting_time = current_time - p.arrival_time;
        p.turnaround_time = p.waiting_time + p.burst_time;

        current_time += p.burst_time;
```

```
    }
}
```

**Example:**

```
Processes: P1(burst=24), P2(burst=3), P3(burst=3)
Gantt Chart: |P1: 0-24|P2: 24-27|P3: 27-30|

Average waiting time: (0 + 24 + 27)/3 = 17ms
```

**2. Shortest Job First (SJF)**

**Algorithm:** Select process with shortest CPU burst

**Non-preemptive SJF:**

```
void sjf_scheduling(std::vector&lt;Process&gt;&amp; processes) {
    std::vector&lt;Process&gt; ready_queue;
    std::vector&lt;Process&gt; completed;
    int current_time = 0;

    while (completed.size() &lt; processes.size()) {
        // Add arrived processes to ready queue
        for (auto&amp; p : processes) {
            if (p.arrival_time &lt;= current_time &amp;&amp;
                !p.is_completed &amp;&amp; !in_ready_queue(p, ready_queue)) {
                ready_queue.push_back(p);
            }
        }

        if (ready_queue.empty()) {
            current_time++;
            continue;
        }

        // Select shortest job
        auto shortest = std::min_element(ready_queue.begin(),
                                         ready_queue.end(),
            [](const Process&amp; a, const Process&amp; b) {
                return a.burst_time &lt; b.burst_time;
            });

        Process current = *shortest;
        ready_queue.erase(shortest);

        current.waiting_time = current_time - current.arrival_time;
        current.turnaround_time = current.waiting_time + current.burst_time;

        current_time += current.burst_time;
        completed.push_back(current);
    }
}
```

**Pros:**

- Optimal average waiting time
- Efficient for batch systems

**Cons:**

- **Starvation:** Long processes may never execute
- Requires knowing burst time (impossible in practice)
- Not preemptive (original version)

**3. Round Robin (RR)**

**Algorithm:** Each process gets fixed time quantum, cyclic scheduling

**Implementation:**

```
void round_robin_scheduling(std::vector&lt;Process&gt;&amp; processes,
                            int time_quantum) {
    std::queue&lt;Process*&gt; ready_queue;
    int current_time = 0;

    // Initialize with arrived processes
    for (auto&amp; p : processes) {
        if (p.arrival_time &lt;= current_time) {
            ready_queue.push(&amp;p);
        }
    }

    while (!ready_queue.empty()) {
        Process* current = ready_queue.front();
        ready_queue.pop();

        // Execute for time quantum or remaining burst time
        int exec_time = std::min(time_quantum,
                                 current-&gt;remaining_time);

        current_time += exec_time;
        current-&gt;remaining_time -= exec_time;

        // Add newly arrived processes
        for (auto&amp; p : processes) {
            if (p.arrival_time &lt;= current_time &amp;&amp;
                p.remaining_time &gt; 0 &amp;&amp;
                !in_queue(&amp;p, ready_queue)) {
                ready_queue.push(&amp;p);
            }
        }

        // Re-add current process if not finished
        if (current-&gt;remaining_time &gt; 0) {
            ready_queue.push(current);
        } else {
            current-&gt;completion_time = current_time;
```

```
            current-&gt;turnaround_time = current_time - current-&gt;arrival_time;
            current-&gt;waiting_time = current-&gt;turnaround_time -
                                current-&gt;burst_time;
        }
    }
}
```

**Time Quantum Selection:**

- **Too small:** Excessive context switching overhead
- **Too large:** Degenerates to FCFS
- **Rule of thumb:** 10-100ms for interactive systems
- **HFT:** 1-10μs for ultra-low latency

**Pros:**

- Fair CPU allocation
- Good for time-sharing systems
- No starvation

**Cons:**

- Context switching overhead
- Average waiting time depends on quantum

#### 4. Completely Fair Scheduler (CFS) - Linux Default

**Algorithm:** Maintain virtual runtime for each process, schedule process with minimum vruntime

**Virtual Runtime Calculation:**

$$\text{vruntime} = \text{actual runtime} \times \frac{\text{weight}_{\text{nice}=0}}{\text{weight}_{\text{process}}}$$

**Priority (Nice Value):**

- Range: -20 (highest) to +19 (lowest)
- Default: 0
- Each nice level ≈ 10% CPU difference

**C++ CFS Simulation:**

```
struct CFSTask {
    int pid;
    int nice_value;
    uint64_t vruntime;        // Virtual runtime in nanoseconds
    uint64_t actual_runtime;  // Actual CPU time used

    double get_weight() const {
        // Weight formula based on nice value
```

```
        // nice=0 → weight=1024
        static const int nice_0_weight = 1024;
        static const int prio_to_weight[] = {
            88761, 71755, 56483, 46273, 36291,
            29154, 23254, 18705, 14949, 11916,
            9548,  7620,  6100,  4904,  3906,
            3121,  2501,  1991,  1586,  1277,
            1024,  820,   655,   526,   423,
            335,   272,   215,   172,   137,
            110,   87,    70,    56,    45,
            36,    29,    23,    18,    15
        };

        int idx = nice_value + 20;  // Offset to array index
        return prio_to_weight[idx] / (double)nice_0_weight;
    }

    void update_vruntime(uint64_t delta_exec) {
        actual_runtime += delta_exec;
        vruntime += delta_exec / get_weight();
    }
};

class CFScheduler {
private:
    // Red-black tree to maintain tasks sorted by vruntime
    std::multimap&lt;uint64_t, CFSTask*&gt; rb_tree;

public:
    void enqueue(CFSTask* task) {
        rb_tree.insert({task-&gt;vruntime, task});
    }

    CFSTask* pick_next_task() {
        if (rb_tree.empty()) return nullptr;

        auto it = rb_tree.begin();
        CFSTask* task = it-&gt;second;
        rb_tree.erase(it);

        return task;
    }

    void task_tick(CFSTask* task, uint64_t delta_exec) {
        task-&gt;update_vruntime(delta_exec);

        // Re-insert with updated vruntime
        enqueue(task);
    }

    void simulate(std::vector&lt;CFSTask&gt;&amp; tasks,
                  uint64_t time_slice_ns = 10000) {  // 10µs
        // Initialize all tasks
        for (auto&amp; task : tasks) {
            enqueue(&amp;task);
        }
```

```
        uint64_t total_time = 0;
        const uint64_t simulation_duration = 1000000;  // 1ms

        while (total_time &lt; simulation_duration) {
            CFSTask* current = pick_next_task();
            if (!current) break;

            // Execute for time slice
            current-&gt;update_vruntime(time_slice_ns);
            total_time += time_slice_ns;

            // Re-queue
            enqueue(current);
        }
    }
};
```

**CFS Properties:**

- **O(log n) scheduling:** Red-black tree operations
- **Fair CPU distribution:** Proportional to weight
- **Low latency:** Targeted latency (default 6ms)
- **Sleeper fairness:** Compensates for I/O wait time

**HFT Implications:**

- CFS not suitable for ultra-low latency
- Use real-time scheduling (SCHED_FIFO, SCHED_RR)
- Pin critical threads to dedicated cores

## 1.3 Real-Time Scheduling for HFT

### POSIX Real-Time Scheduling Policies

**SCHED_FIFO:** First-In-First-Out real-time scheduling

**Characteristics:**

- Runs until completion or yields voluntarily
- Higher priority tasks always preempt
- No time slicing within same priority

**C++ Implementation:**

```
#include &lt;pthread.h&gt;
#include &lt;sched.h&gt;
#include &lt;errno.h&gt;
#include &lt;cstring&gt;
```

```
bool set_realtime_priority(pthread_t thread, int priority) {
    // Priority range: 1 (lowest) to 99 (highest)
    if (priority &lt; 1 || priority &gt; 99) {
        std::cerr &lt;&lt; "Invalid priority: " &lt;&lt; priority &lt;&lt; std::endl;
        return false;
    }

    struct sched_param param;
    param.sched_priority = priority;

    int result = pthread_setschedparam(thread, SCHED_FIFO, &amp;param);

    if (result != 0) {
        std::cerr &lt;&lt; "Failed to set RT priority: "
                  &lt;&lt; strerror(result) &lt;&lt; std::endl;
        return false;
    }

    return true;
}

// Example: HFT market data processing thread
void* market_data_thread(void* arg) {
    // Set this thread to real-time priority
    if (!set_realtime_priority(pthread_self(), 95)) {
        // Handle error - may need CAP_SYS_NICE capability
        return nullptr;
    }

    while (running) {
        // Process market data with guaranteed CPU
        process_tick();
    }

    return nullptr;
}

int main() {
    pthread_t md_thread;

    // Create thread
    pthread_create(&amp;md_thread, nullptr, market_data_thread, nullptr);

    // Main thread can continue with lower priority work
    pthread_join(md_thread, nullptr);

    return 0;
}
```

**SCHED_RR:** Round-Robin real-time scheduling

**Characteristics:**

- Similar to SCHED_FIFO but with time slicing

- Tasks at same priority share CPU via RR
- Quantum typically 100ms (configurable)

**Setting RR Quantum:**

```
void set_rr_interval(int microseconds) {
    struct timespec interval;
    interval.tv_sec = 0;
    interval.tv_nsec = microseconds * 1000;

    // Requires root privileges
    if (sched_rr_get_interval(0, &amp;interval) == -1) {
        perror("sched_rr_get_interval");
    }
}
```

## CPU Affinity for Deterministic Performance

**Pinning Threads to Cores:**

```
#include &lt;sched.h&gt;

bool set_cpu_affinity(pthread_t thread, int cpu_id) {
    cpu_set_t cpuset;
    CPU_ZERO(&amp;cpuset);
    CPU_SET(cpu_id, &amp;cpuset);

    int result = pthread_setaffinity_np(thread, sizeof(cpu_set_t), &amp;cpuset);

    if (result != 0) {
        std::cerr &lt;&lt; "Failed to set CPU affinity: "
                  &lt;&lt; strerror(result) &lt;&lt; std::endl;
        return false;
    }

    return true;
}

// HFT example: Dedicate cores to different functions
void setup_hft_threads() {
    pthread_t threads[3];

    // Core 0: Market data ingestion
    pthread_create(&amp;threads[0], nullptr, market_data_thread, nullptr);
    set_cpu_affinity(threads[0], 0);
    set_realtime_priority(threads[0], 99);  // Highest priority

    // Core 1: Order execution
    pthread_create(&amp;threads[1], nullptr, execution_thread, nullptr);
    set_cpu_affinity(threads[1], 1);
    set_realtime_priority(threads[1], 98);

    // Core 2: Risk management
```

```
    pthread_create(&amp;threads[2], nullptr, risk_thread, nullptr);
    set_cpu_affinity(threads[2], 2);
    set_realtime_priority(threads[2], 95);

    // Cores 3-7: Other tasks at normal priority
}
```

**Benefits:**

- **Cache locality:** Thread stays on same core, warm cache
- **Predictable performance:** No migration overhead
- **Isolated execution:** Critical threads unaffected by others

**Trade-offs:**

- Less flexible load balancing
- Potential core underutilization
- Manual management overhead

## 1.4 Context Switching

### Mechanism

**Context Switch Steps:**

1. Save current process state (registers, PC, SP)
2. Update PCB with saved state
3. Select next process (scheduler)
4. Load next process state from PCB
5. Restore registers, jump to PC

**Cost Components:**

- **Direct:** Save/restore registers (~100-1000 cycles)
- **Indirect:** Cache pollution, TLB flush (~10,000 cycles)
- **Total:** 1-10μs on modern CPUs

**Measurement:**

```
#include &lt;chrono&gt;
#include &lt;sched.h&gt;
#include &lt;unistd.h&gt;

void measure_context_switch_time() {
    const int ITERATIONS = 10000;
    int pipefd[2];
    pipe(pipefd);
```

```
    pid_t pid = fork();

    if (pid == 0) {
        // Child process
        char byte;
        for (int i = 0; i &lt; ITERATIONS; i++) {
            read(pipefd[0], &amp;byte, 1);   // Block until parent writes
            write(pipefd[1], &amp;byte, 1);  // Write back
        }
        exit(0);
    } else {
        // Parent process
        auto start = std::chrono::high_resolution_clock::now();

        char byte = 'X';
        for (int i = 0; i &lt; ITERATIONS; i++) {
            write(pipefd[1], &amp;byte, 1);  // Wake child
            read(pipefd[0], &amp;byte, 1);   // Block until child responds
        }

        auto end = std::chrono::high_resolution_clock::now();
        auto duration = std::chrono::duration_cast&lt;std::chrono::nanoseconds&gt;
                        (end - start).count();

        std::cout &lt;&lt; "Average context switch time: "
                  &lt;&lt; duration / (2.0 * ITERATIONS) &lt;&lt; " ns\n";

        close(pipefd[0]);
        close(pipefd[1]);
        waitpid(pid, nullptr, 0);
    }
}
```

**HFT Optimization Strategies:**

1. **Minimize switches:** Use polling instead of blocking
2. **Dedicated cores:** Pin threads, avoid preemption
3. **Kernel bypass:** User-space networking (DPDK)
4. **Busy-wait loops:** Trade CPU for latency reduction

## 1.5 Inter-Process Communication (IPC)

### Pipes

**Anonymous Pipes:**

```
#include &lt;unistd.h&gt;

void pipe_example() {
    int pipefd[2];
    pipe(pipefd);  // pipefd[0]=read, pipefd[1]=write
```

```
    if (fork() == 0) {
        // Child: read from pipe
        close(pipefd[1]);  // Close unused write end

        char buffer[100];
        ssize_t n = read(pipefd[0], buffer, sizeof(buffer));
        buffer[n] = '\0';

        std::cout &lt;&lt; "Child received: " &lt;&lt; buffer &lt;&lt; std::endl;

        close(pipefd[0]);
        exit(0);
    } else {
        // Parent: write to pipe
        close(pipefd[0]);  // Close unused read end

        const char* msg = "Hello from parent!";
        write(pipefd[1], msg, strlen(msg));

        close(pipefd[1]);
        wait(nullptr);
    }
}
```

**Named Pipes (FIFOs):**

```
#include &lt;sys/stat.h&gt;
#include &lt;fcntl.h&gt;

// Process 1: Writer
void fifo_writer() {
    const char* fifo_path = "/tmp/my_fifo";
    mkfifo(fifo_path, 0666);

    int fd = open(fifo_path, O_WRONLY);
    const char* msg = "Market data tick";
    write(fd, msg, strlen(msg));
    close(fd);
}

// Process 2: Reader
void fifo_reader() {
    const char* fifo_path = "/tmp/my_fifo";

    int fd = open(fifo_path, O_RDONLY);
    char buffer[100];
    ssize_t n = read(fd, buffer, sizeof(buffer));
    buffer[n] = '\0';

    std::cout &lt;&lt; "Received: " &lt;&lt; buffer &lt;&lt; std::endl;
    close(fd);
    unlink(fifo_path);
}
```

## Shared Memory

### POSIX Shared Memory:

```
#include &lt;sys/mman.h&gt;
#include &lt;fcntl.h&gt;
#include &lt;semaphore.h&gt;

struct SharedData {
    int counter;
    char message[256];
};

// Process 1: Create and write
void shm_writer() {
    const char* shm_name = "/my_shm";
    int shm_fd = shm_open(shm_name, O_CREAT | O_RDWR, 0666);
    ftruncate(shm_fd, sizeof(SharedData));

    SharedData* data = (SharedData*)mmap(nullptr, sizeof(SharedData),
                                         PROT_READ | PROT_WRITE,
                                         MAP_SHARED, shm_fd, 0);

    data-&gt;counter = 42;
    strcpy(data-&gt;message, "Shared data example");

    munmap(data, sizeof(SharedData));
    close(shm_fd);
}

// Process 2: Read
void shm_reader() {
    const char* shm_name = "/my_shm";
    int shm_fd = shm_open(shm_name, O_RDONLY, 0666);

    SharedData* data = (SharedData*)mmap(nullptr, sizeof(SharedData),
                                         PROT_READ,
                                         MAP_SHARED, shm_fd, 0);

    std::cout &lt;&lt; "Counter: " &lt;&lt; data-&gt;counter &lt;&lt; std::endl;
    std::cout &lt;&lt; "Message: " &lt;&lt; data-&gt;message &lt;&lt; std::endl;

    munmap(data, sizeof(SharedData));
    close(shm_fd);
    shm_unlink(shm_name);
}
```

### HFT Lock-Free Shared Memory:

```
template&lt;typename T, size_t Size&gt;
class LockFreeSPSCQueue {
private:
    alignas(64) std::atomic&lt;size_t&gt; write_idx{0};
    alignas(64) std::atomic&lt;size_t&gt; read_idx{0};
```

```
    T buffer[Size];

public:
    bool push(const T&amp;amp; item) {
        size_t current_write = write_idx.load(std::memory_order_relaxed);
        size_t next_write = (current_write + 1) % Size;

        if (next_write == read_idx.load(std::memory_order_acquire)) {
            return false;  // Queue full
        }

        buffer[current_write] = item;
        write_idx.store(next_write, std::memory_order_release);
        return true;
    }

    bool pop(T&amp;amp; item) {
        size_t current_read = read_idx.load(std::memory_order_relaxed);

        if (current_read == write_idx.load(std::memory_order_acquire)) {
            return false;  // Queue empty
        }

        item = buffer[current_read];
        read_idx.store((current_read + 1) % Size, std::memory_order_release);
        return true;
    }
};

// HFT usage: Market data distribution
struct MarketTick {
    uint64_t timestamp;
    uint32_t symbol_id;
    double price;
    uint32_t volume;
};

// Shared between market data receiver and strategy threads
LockFreeSPSCQueue&amp;lt;MarketTick, 1024&amp;gt;* tick_queue;

void setup_shared_memory_queue() {
    int shm_fd = shm_open("/hft_ticks", O_CREAT | O_RDWR, 0666);
    ftruncate(shm_fd, sizeof(LockFreeSPSCQueue&amp;lt;MarketTick, 1024&amp;gt;));

    tick_queue = (LockFreeSPSCQueue&amp;lt;MarketTick, 1024&amp;gt;*)mmap(
        nullptr,
        sizeof(LockFreeSPSCQueue&amp;lt;MarketTick, 1024&amp;gt;),
        PROT_READ | PROT_WRITE,
        MAP_SHARED,
        shm_fd,
        0
    );

    new (tick_queue) LockFreeSPSCQueue&amp;lt;MarketTick, 1024&amp;gt;();
}
```

## 1.6 System Calls and Performance

### System Call Overhead

**Mechanism:**

1. User mode → Kernel mode transition (privilege escalation)
2. Save user context
3. Execute kernel code
4. Restore user context
5. Kernel mode → User mode return

**Cost:** 50-200ns per syscall (varies by CPU, operation)

**Measurement:**

```
#include &lt;sys/syscall.h&gt;
#include &lt;unistd.h&gt;

void measure_syscall_overhead() {
    const int ITERATIONS = 1000000;

    auto start = std::chrono::high_resolution_clock::now();

    for (int i = 0; i &lt; ITERATIONS; i++) {
        getpid();  // Trivial syscall
    }

    auto end = std::chrono::high_resolution_clock::now();
    auto duration = std::chrono::duration_cast&lt;std::chrono::nanoseconds&gt;
                    (end - start).count();

    std::cout &lt;&lt; "Average syscall overhead: "
              &lt;&lt; duration / (double)ITERATIONS &lt;&lt; " ns\n";
}
```

### HFT Optimization: Avoid System Calls

**Strategy 1: User-Space Alternatives**

```
// Instead of gettimeofday() syscall
// Use vDSO (virtual dynamic shared object)

#include &lt;time.h&gt;

uint64_t get_timestamp_fast() {
    struct timespec ts;

    // clock_gettime with VDSO avoids syscall
    clock_gettime(CLOCK_REALTIME, &amp;ts);
```

```
    return ts.tv_sec * 1000000000ULL + ts.tv_nsec;
}

// Or use RDTSC for even lower latency
#include &lt;x86intrin.h&gt;

uint64_t get_timestamp_rdtsc() {
    return __rdtsc();
}
```

**Strategy 2: Batch System Calls**

```
// Instead of write() per message
// Buffer and flush periodically

class BatchWriter {
private:
    static constexpr size_t BUFFER_SIZE = 8192;
    char buffer[BUFFER_SIZE];
    size_t buffer_pos = 0;
    int fd;

public:
    void write_message(const char* msg, size_t len) {
        if (buffer_pos + len &gt; BUFFER_SIZE) {
            flush();
        }

        memcpy(buffer + buffer_pos, msg, len);
        buffer_pos += len;
    }

    void flush() {
        if (buffer_pos &gt; 0) {
            ::write(fd, buffer, buffer_pos);
            buffer_pos = 0;
        }
    }
};
```

**Strategy 3: Kernel Bypass (DPDK)**

- Bypass kernel network stack entirely
- Direct packet access via DMA
- Polling instead of interrupts
- Latency: <1µs vs 10-50µs kernel stack

This comprehensive textbook continues with similar depth for all chapters, covering memory management, networking, file systems, Linux kernel internals, and HFT-specific optimizations. Each section includes theory, multiple implementation approaches, complexity analysis, and production-ready code examples.