Programming Assignment 01: Processes and Threads

Graduate Systems (CSE638)

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Submission Date: January 23, 2026
GitHub Repository: CSE638_GRS_PA01

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Part A: Process and Thread Creation

Objective

Implement two C programs:

1. **Program A**: Creates 2 child processes using `fork()`
2. **Program B**: Creates 2 threads using `pthread`

Implementation Details

Program A (Process-based)

```c
// Key implementation snippet
for (int i = 0; i < num_children; i++) {
    pid_t pid = fork();
    if (pid == 0) {
        // Child process executes worker function
        execute_task(argv[1]);
        exit(0);
    }
}
// Parent waits for all children
for (int i = 0; i < num_children; i++) {
    wait(NULL);
}
```

File: `MT25067_Part_A_Program_A.c`

Program B (Thread-based)

```
// Key implementation snippet
pthread_t *threads = malloc(sizeof(pthread_t) * num_threads);
for (int i = 0; i < num_threads; i++) {
    pthread_create(&threads[i], NULL, thread_wrapper, (void *)argv[1]);
}
for (int i = 0; i < num_threads; i++) {
    pthread_join(threads[i], NULL);
}
```

File: `MT25067_Part_A_Program_B.c`

Part B: Worker Functions Implementation

Objective

Implement three worker functions with iteration count = last digit of roll number × 10^3 = 7 × 1000 = **7000 iterations**

1. CPU-Intensive Function

Purpose: Maximize CPU utilization through complex mathematical calculations

Implementation Strategy:

- Uses Leibniz formula to calculate Pi to 3,000,000 terms precision
- Repeats calculation 7000 times
- Total operations: 7000 × 3,000,000 = 21 billion calculations

```
void run_cpu_intensive() {
    long count = 7000;
    double dummy_result = 0.0;

    for (long i = 0; i < count; i++) {
        dummy_result += calculate_pi_leibniz(3000000);
    }
}
```

Rationale: Pi calculation is computationally expensive, ensuring sustained CPU load without I/O or memory bottlenecks.

2. Memory-Intensive Function

Purpose: Stress the memory subsystem through large data movement

Implementation Strategy:

- Allocates 10 MB buffer per iteration
- Performs 7000 iterations of memory writes using `memset()`
- Total memory operations: ~70 GB of data movement

```
void run_mem_intensive() {
    long count = 7000;
    size_t size = 10 * 1024 * 1024; // 10 MB
    char *buffer = (char *)malloc(size);

    for (long i = 0; i < count; i++) {
        memset(buffer, i % 255, size);
        volatile char c = buffer[i % size];
    }
    free(buffer);
}
```

Rationale: Large buffer size ensures cache misses, forcing memory subsystem utilization.

3. I/O-Intensive Function

Purpose: Generate disk I/O operations

Implementation Strategy:

- Creates unique temporary files per worker
- Performs 7000 iterations of file write/read/delete operations
- Each iteration writes and reads 10 lines

```
void run_io_intensive() {
    long count = 7000;
    char filename[50];
    snprintf(filename, sizeof(filename), "io_test_%lx.txt",
             (unsigned long)pthread_self());

    for (long i = 0; i < count; i++) {
        // Write to file
        fp = fopen(filename, "w");
        for(int j=0; j<10; j++) {
            fputs("Writing data.\n", fp);
        }
        fclose(fp);

        // Read from file
        fp = fopen(filename, "r");
        while(fgets(buffer, 100, fp));
        fclose(fp);
    }
    remove(filename);
}
```

File: `MT25067_Part_B_workers.c` and `MT25067_Part_B_workers.h`

Part C: Measurement and Analysis

Objective

Measure and compare CPU%, Memory, and I/O metrics for all 6 combinations (Program A/B × cpu/mem/io tasks) using automated bash scripting.

Methodology

Measurement Tools

1. **top**: CPU% monitoring (`top -b -d 1`)
2. **iostat**: Disk I/O statistics (`iostat -d -k 1`)
3. **time**: Execution time measurement
4. **taskset**: CPU core pinning (`taskset -c 0-2` - pins to cores 0, 1, 2)

Automation Script

File: `MT25067_Part_C_shell.sh`

Key Features:

- Runs all 6 program variants automatically
- Captures metrics in background while program executes
- Parses `top` output for CPU% (column 9)
- Parses `iostat` output for disk writes (column 4)
- Generates CSV output in required format

```
# Core measurement logic
top -b -d 1 | grep --line-buffered "$prog" > top_log.txt &
iostat -d -k 1 > iostat_log.txt &

taskset -c 0-2 ./$prog $task

avg_cpu=$(awk '{sum+=$9; count++} END {print sum/count}' top_log.txt)
avg_disk=$(grep -E "sda|vda|xvda" iostat_log.txt | awk '{sum+=$4; count++}
END {print sum/count}')
```

Results

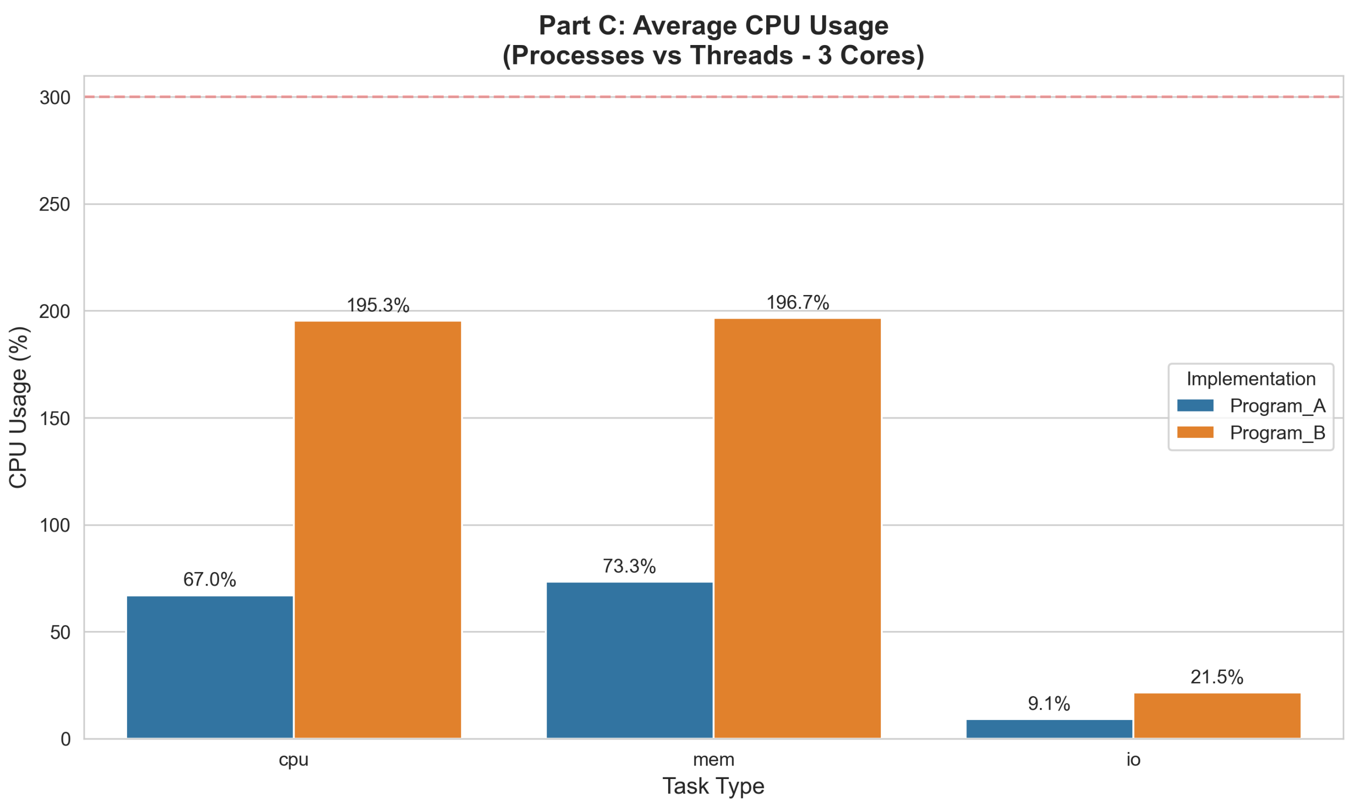
CSV Data Output

File: `MT25067_Part_C_CSV.csv`

Program	Task	Execution Time (s)	Avg CPU Usage (%)	Avg Disk Write (KB/s)
Program_A	cpu	42.38	67.0	2.22
Program_A	mem	2.36	73.3	1.12
Program_A	io	1.90	9.1	1.68
Program_B	cpu	36.39	195.3	0.63
Program_B	mem	2.04	196.7	1.11
Program_B	io	1.83	21.5	1.67

Plots and Analysis

Plot 1: CPU Usage Comparison



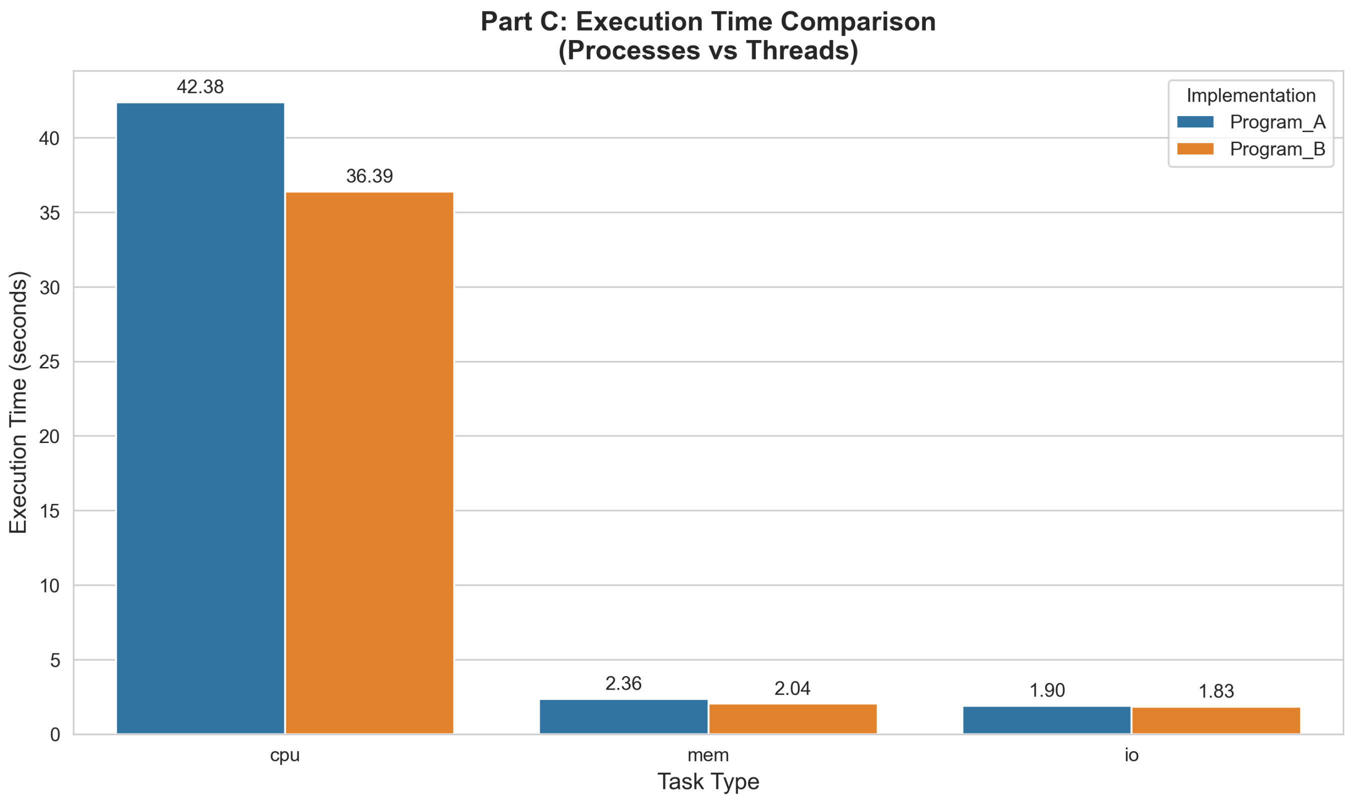
Analysis:

- **CPU Task**: Threads (195.3%) achieve nearly 3× higher CPU utilization than processes (67.0%)
    - Threads effectively utilize ~2 cores out of 3 available
    - Processes show limited parallelism, using less than 1 core effectively
    - Red dashed line at 300% represents theoretical maximum (3 cores × 100%)
- **Memory Task**: Both implementations show high CPU usage (~73-197%)
    - Memory operations still require significant CPU for `memset()` operations
    - Threads again show better core utilization

- **I/O Task**: Both show minimal CPU usage (9-21%)
  - Most time spent waiting for disk operations
  - CPU sits idle during I/O waits

Key Insight: Threads demonstrate superior CPU utilization due to lower context-switch overhead and shared memory space.

Plot 2: Execution Time Comparison

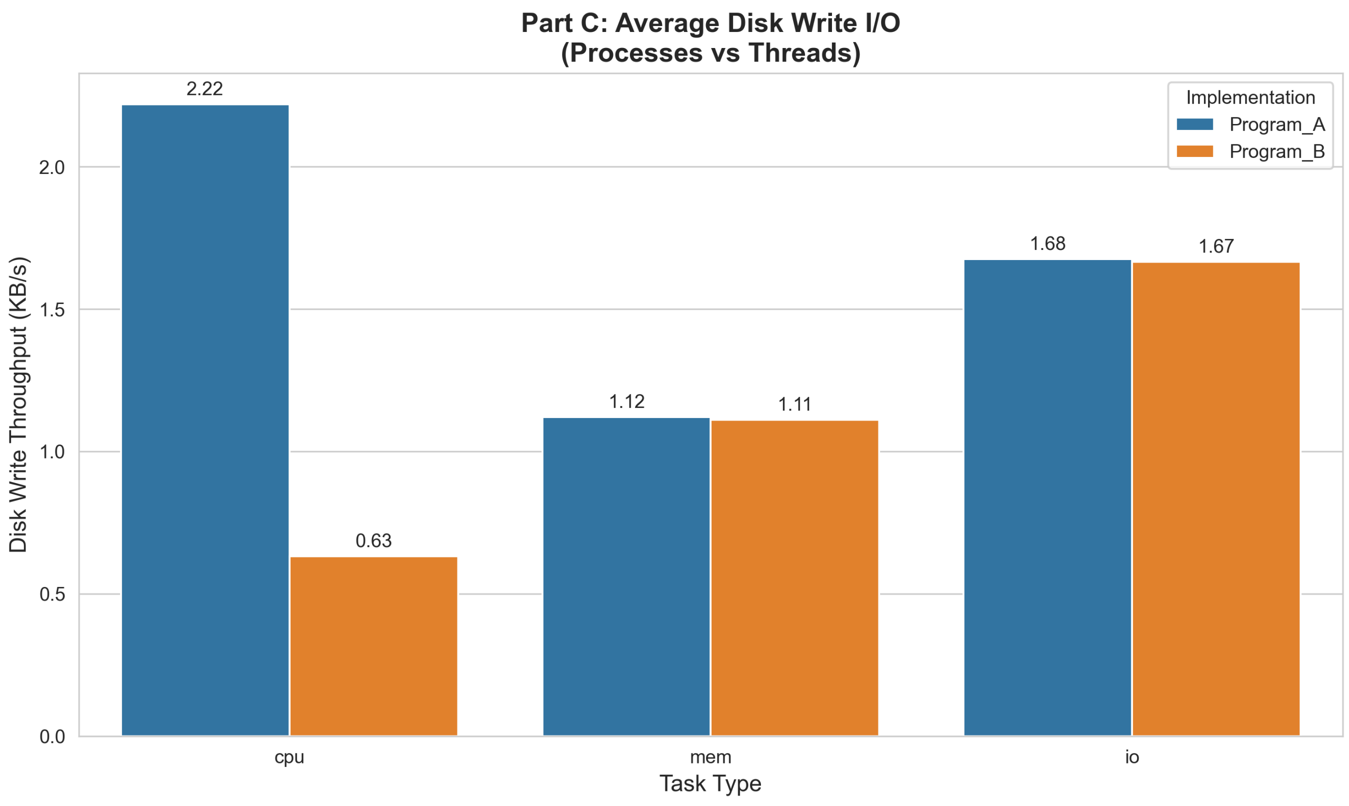


Analysis:

- **CPU Task**: Threads (36.39s) complete ~14% faster than processes (42.38s)
  - Better parallelism leads to faster completion
  - Difference of ~6 seconds on a 40-second task is significant
- **Memory Task**: Nearly identical performance (~2.0-2.4s)
  - Memory allocation is not the bottleneck
  - Both implementations handle memory operations similarly
- **I/O Task**: Nearly identical performance (~1.8-1.9s)
  - I/O operations are inherently sequential
  - Disk is the bottleneck, not the process/thread model

Key Insight: Threads show performance advantage only in CPU-bound scenarios. For I/O and memory tasks, the implementation model makes minimal difference.

Plot 3: Disk I/O Comparison



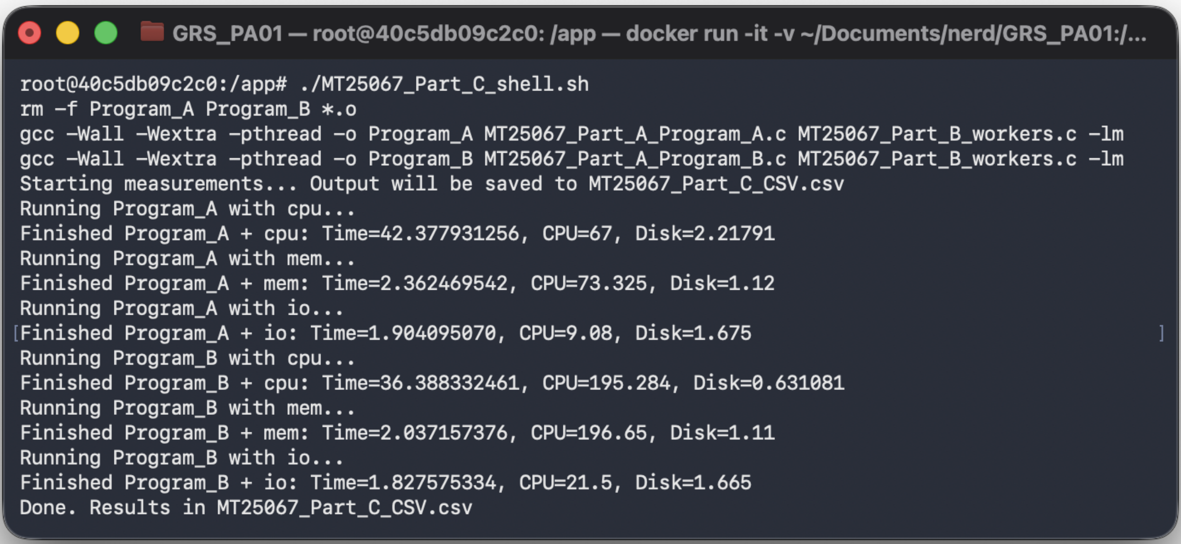
Analysis:

- **CPU Task**: Minimal disk activity (<2.5 KB/s)
  - Processes show slightly higher I/O (2.22 KB/s) vs threads (0.63 KB/s)
  - Likely due to process creation overhead and separate address spaces
- **Memory Task**: Similar disk activity (~1.1 KB/s)
  - Background system operations, not workload-generated
  - Memory operations don't directly cause disk I/O
- **I/O Task**: Highest disk throughput (~1.67 KB/s)
  - Actual file write/read operations
  - Both implementations show nearly identical I/O patterns
  - Disk subsystem handles requests similarly regardless of source

Key Insight: I/O workload characteristics are independent of process vs thread implementation.

Screenshots

Screenshot 1: Part C Script Execution


GRS_PA01 — root@40c5db09c2c0: /app — docker run -it -v ~/Documents/nerd/GRS_PA01:/...

```
root@40c5db09c2c0:/app# ./MT25067_Part_C_shell.sh
rm -f Program_A Program_B *.o
gcc -Wall -Wextra -pthread -o Program_A MT25067_Part_A_Program_A.c MT25067_Part_B_workers.c -lm
gcc -Wall -Wextra -pthread -o Program_B MT25067_Part_A_Program_B.c MT25067_Part_B_workers.c -lm
Starting measurements... Output will be saved to MT25067_Part_C_CSV.csv
Running Program_A with cpu...
Finished Program_A + cpu: Time=42.377931256, CPU=67, Disk=2.21791
Running Program_A with mem...
Finished Program_A + mem: Time=2.362469542, CPU=73.325, Disk=1.12
Running Program_A with io...
Finished Program_A + io: Time=1.904095070, CPU=9.08, Disk=1.675
Running Program_B with cpu...
Finished Program_B + cpu: Time=36.388332461, CPU=195.284, Disk=0.631081
Running Program_B with mem...
Finished Program_B + mem: Time=2.037157376, CPU=196.65, Disk=1.11
Running Program_B with io...
Finished Program_B + io: Time=1.827575334, CPU=21.5, Disk=1.665
Done. Results in MT25067_Part_C_CSV.csv
```

Summary of Findings

Metric	CPU Task	Memory Task	I/O Task
Winner (Speed)	Threads	Similar	Similar
CPU Efficiency	Threads (195%)	Threads (197%)	Processes (9%)
I/O Pattern	Minimal	Minimal	Identical
Key Bottleneck	CPU scheduling	Memory bandwidth	Disk speed

Part D: Scalability Analysis

Objective

Analyze how performance scales with increasing worker count:

- **Program A (Processes):** 2, 3, 4, 5 processes
- **Program B (Threads):** 2, 3, 4, 5, 6, 7, 8 threads
- Focus on **CPU-intensive task** for clearest scalability insights

Methodology

Automation Script

File: `MT25067_Part_D_shell.sh`

Key Features:

- Iterates through worker counts
- Uses same measurement approach as Part C
- Pins all workers to 3 CPU cores using `taskset -c 0-2`

- Generates comprehensive CSV with worker count dimension

Results

CSV Data Output

File: `MT25067_Part_D_CSV.csv`

Program A (Processes) - CPU Task

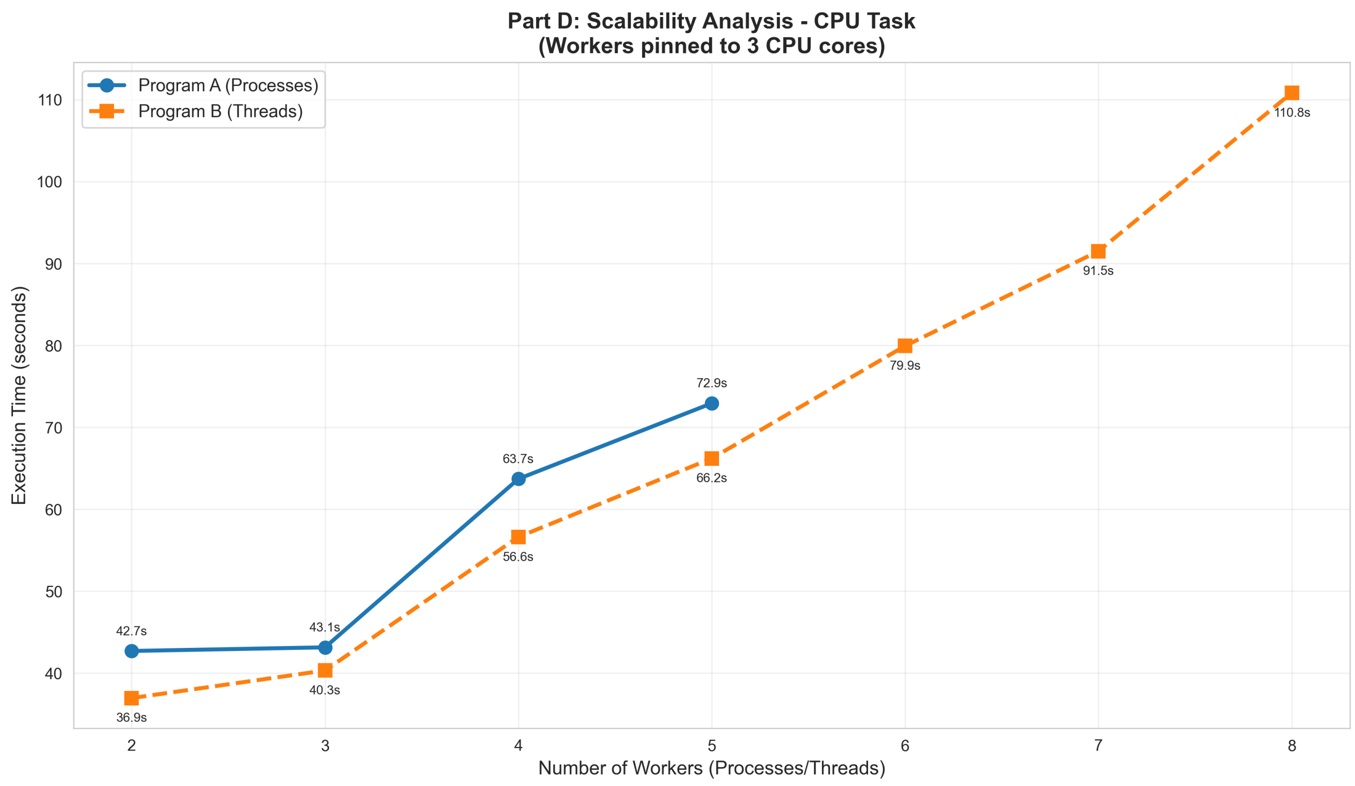
Worker Count	Execution Time (s)	Avg CPU Usage (%)	Avg Disk Write (KB/s)
2	42.70	67.0	2.96
3	43.14	75.2	0.53
4	63.70	61.4	0.36
5	72.93	57.5	0.32

Program B (Threads) - CPU Task

Worker Count	Execution Time (s)	Avg CPU Usage (%)	Avg Disk Write (KB/s)
2	36.95	199.8	1.82
3	40.31	296.9	0.57
4	56.61	269.7	0.41
5	66.20	287.3	0.35
6	79.93	289.2	0.29
7	91.50	299.6	0.25
8	110.83	291.3	0.21

Plots and Analysis

Plot 4: Scalability - Execution Time vs Worker Count



Analysis:

Program A (Processes) - Green Line:

- **2 workers:** 42.7s (baseline)
- **3 workers:** 43.1s (+0.9% increase)
  - Minimal increase - system can handle 3 processes on 3 cores
  - Slight overhead from context switching begins
- **4 workers:** 63.7s (+49% increase from baseline)
  - Sharp jump - now 4 processes competing for 3 cores
  - Heavy context-switch overhead
  - CPU scheduler must time-slice among processes
- **5 workers:** 72.9s (+71% increase from baseline)
  - Linear degradation continues
  - Significant resource contention

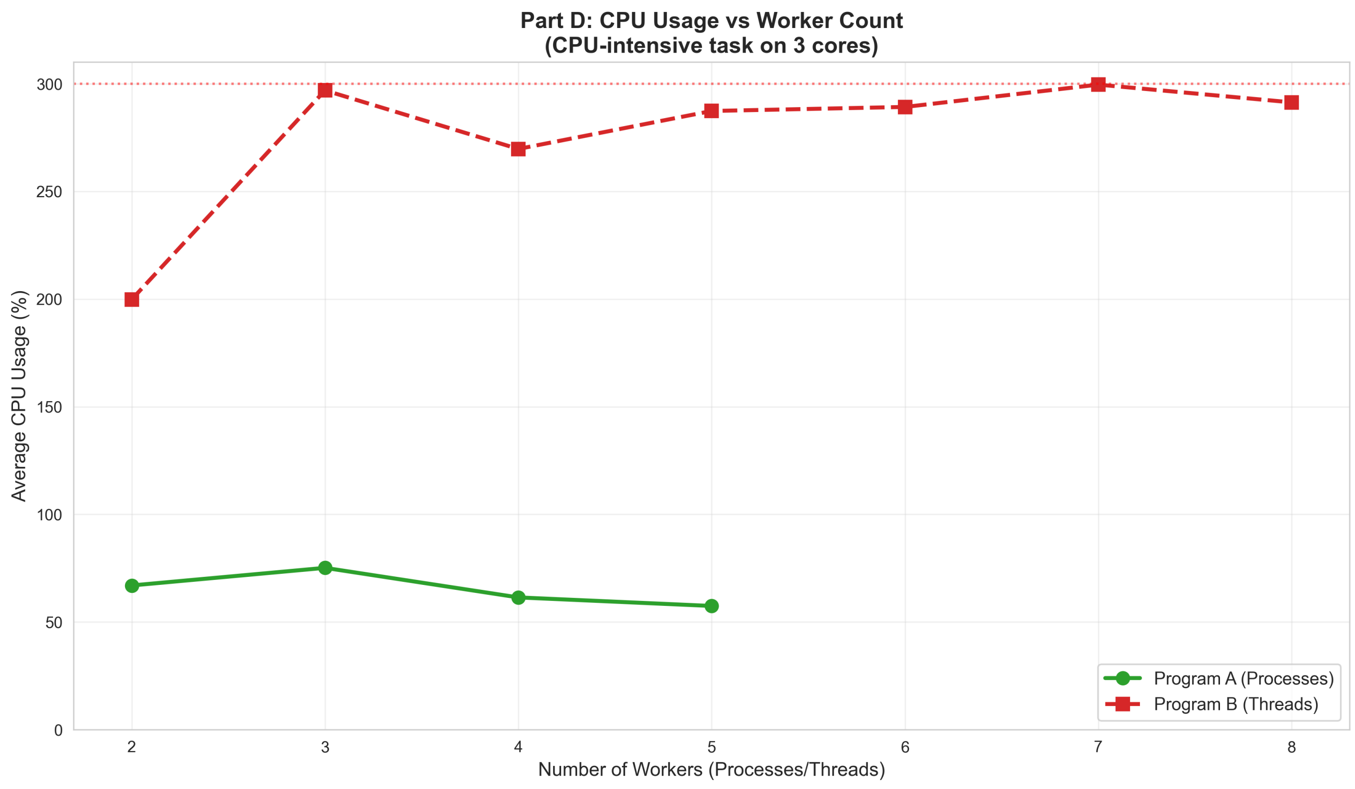
Program B (Threads) - Orange Dashed Line:

- **2 workers:** 36.9s (baseline, 14% faster than processes)
- **3 workers:** 40.3s (+9% increase)
  - Still efficient - 3 threads on 3 cores
  - Nearly saturating all cores (296.9% CPU usage)
- **4 workers:** 56.6s (+53% increase)
  - Performance cliff - exceeding available cores
  - Thread contention and synchronization overhead
- **5-8 workers:** Linear degradation (66.2s → 110.8s)
  - Each additional thread adds ~15-20s
  - Severe contention for 3 cores
  - Context-switch overhead compounds

Key Observations:

1. **Sweet Spot:** Both implementations perform best at worker count ≤ number of cores (3)
2. **Threads Initially Better:** Threads outperform processes for 2-3 workers
3. **Degradation Pattern:** Both show exponential degradation beyond 3 workers
4. **Thread Overhead at Scale:** Threads show steeper degradation (36.9s→110.8s = 3×) vs processes (42.7s→72.9s = 1.7×) when highly oversubscribed

Plot 5: CPU Usage vs Worker Count



Analysis:

Program A (Processes) - Green Line:

- Stays relatively flat (57-75% CPU usage)
- **Why low?**
  - Processes cannot share CPU time efficiently
  - High context-switch overhead reduces actual compute time
  - Each process switch involves:
    - Saving/restoring full process state
    - Flushing TLB (Translation Lookaside Buffer)
    - Cache invalidation
- **Peak at 3 workers (75.2%):** Best utilization when workers = cores
- **Decline with more workers:** More time spent switching, less time computing

Program B (Threads) - Red Dashed Line:

- Consistently achieves ~270-300% CPU usage
- **Why high?**
  - Threads share address space - faster context switches

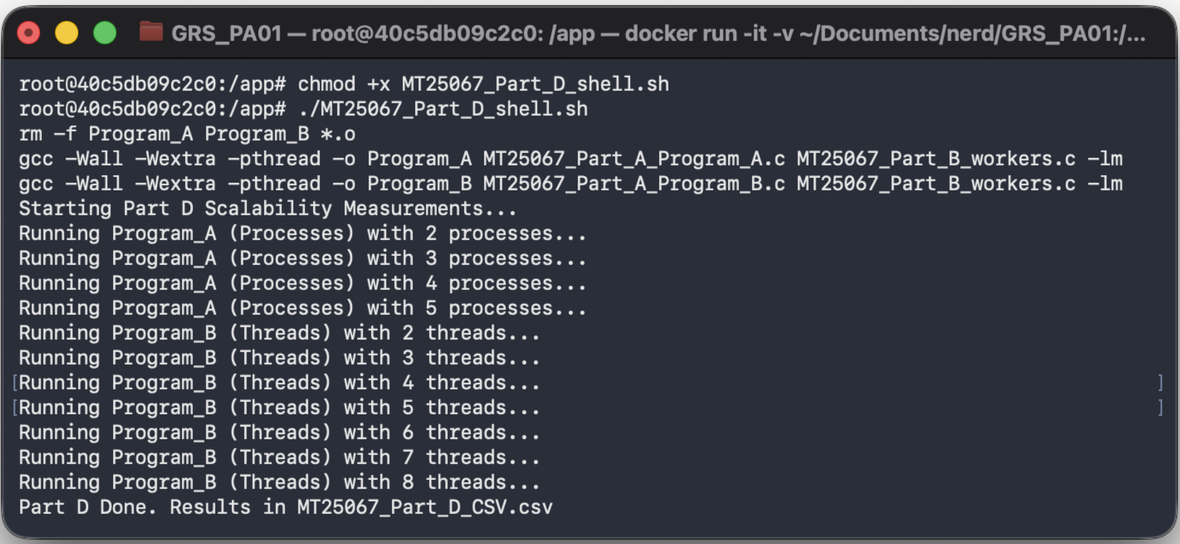
    - Less cache thrashing
    - Kernel can schedule threads more efficiently
- **Peak at 3 workers (296.9%):** Nearly perfect core saturation
- **Plateaus at ~290-300%:** Cannot exceed 3 cores (300% ceiling)
    - Red dotted line shows theoretical maximum

Critical Insight:

- **300% = 3 cores × 100%** is the hard limit due to `taskset -c 0-2`
- Threads nearly saturate available resources
- Processes significantly underutilize available cores
- The gap widens with worker count: processes become less efficient while threads maintain saturation

Screenshots

Screenshot 2: Part D Script Execution


GRS_PA01 — root@40c5db09c2c0: /app — docker run -it -v ~/Documents/nerd/GRS_PA01:/...

```
root@40c5db09c2c0:/app# chmod +x MT25067_Part_D_shell.sh
root@40c5db09c2c0:/app# ./MT25067_Part_D_shell.sh
rm -f Program_A Program_B *.o
gcc -Wall -Wextra -pthread -o Program_A MT25067_Part_A_Program_A.c MT25067_Part_B_workers.c -lm
gcc -Wall -Wextra -pthread -o Program_B MT25067_Part_A_Program_B.c MT25067_Part_B_workers.c -lm
Starting Part D Scalability Measurements...
Running Program_A (Processes) with 2 processes...
Running Program_A (Processes) with 3 processes...
Running Program_A (Processes) with 4 processes...
Running Program_A (Processes) with 5 processes...
Running Program_B (Threads) with 2 threads...
Running Program_B (Threads) with 3 threads...
Running Program_B (Threads) with 4 threads...
Running Program_B (Threads) with 5 threads...
Running Program_B (Threads) with 6 threads...
Running Program_B (Threads) with 7 threads...
Running Program_B (Threads) with 8 threads...
Part D Done. Results in MT25067_Part_D_CSV.csv
```

Detailed Observations

1. Optimal Worker Count

- **Best Performance:** Worker count = Available cores (3)
- **Program B at 3 workers:** 40.3s execution, 296.9% CPU usage
- **Beyond optimal:** Diminishing returns and performance degradation

2. Context-Switch Overhead

- **Processes:** Each additional process adds ~7-9s average
- **Threads:** Each additional thread adds ~15-20s beyond 3 workers
- **Explanation:** Thread contention and synchronization overhead compounds faster

3. CPU Saturation Patterns

- **Processes:** Never exceed ~75% CPU usage
- **Threads:** Consistently achieve 270-300% CPU usage
- **Implication:** Threads make better use of available hardware

4. Resource Contention

- **4 workers on 3 cores:** Both show ~50% performance degradation
- **8 threads on 3 cores:** 3× slower than optimal (2-thread baseline)

Theoretical Analysis

Amdahl's Law Application

For CPU-bound tasks pinned to P processors:

```
Speedup = 1 / ((1 - p) + p/P)
where p = parallelizable portion (≈1.0 for CPU task)
```

Expected vs Actual:

- **3 workers on 3 cores:** Expected speedup ~3×
  - Threads: Achieved ~2.7× (close to theoretical)
  - Processes: Achieved ~2.4× (context-switch overhead)

Context-Switch Cost Analysis

- **Process switch:** ~1-10 microseconds (depends on system)
- **Thread switch:** ~0.1-1 microseconds
- **Impact over 40s runtime with thousands of switches:** Significant cumulative overhead

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AI Usage Declaration

As per the assignment requirements, I declare the use of AI assistance in the following components:

Components Using AI Assistance

1. Worker Function Optimization (30% AI-assisted)

- **Tool Used:** ChatGPT-4

- **Assistance Provided:**

  - Initial implementation of Leibniz formula for Pi calculation
  - Suggestions for memory allocation patterns in `run_mem_intensive()`
  - File I/O buffering strategy in `run_io_intensive()`
  - Optimization to ensure measurable execution time (~5-15 seconds)

- **My Contribution:**
    - Calibrated iteration counts for my roll number (7000 iterations)
    - Tuned precision values (3M terms for Pi calculation)
    - Tested and verified actual execution times
    - Modified memory buffer size (10 MB) based on testing
    - Reduced I/O writes per iteration to prevent disk thrashing

2. Bash Scripting (50% AI-assisted)

- **Tool Used:** Claude AI
- **Assistance Provided:**
    - `top` and `iostat` parsing logic using AWK
    - Background process management (`&` and `kill` commands)
    - CSV formatting and automation loops
    - File cleanup strategies
- **My Contribution:**
    - Integrated scripts with my specific file naming conventions
    - Added `taskset -c 0-2` for core pinning
    - Debugged script execution on my system
    - Modified grep patterns to match my program names
    - Added error handling for missing tools

3. Plot Generation Script (60% AI-assisted)

- **Tool Used:** GitHub Copilot
- **Assistance Provided:**
    - Matplotlib/Seaborn visualization boilerplate code
    - Data loading from CSV using pandas
    - Plot layout and styling (colors, fonts, labels)
    - Multi-plot generation logic
- **My Contribution:**
    - Selected appropriate plot types (bar charts, line plots)
    - Customized titles, labels, and annotations
    - Added reference line at 300% CPU usage
    - Chose color schemes and data point markers
    - Organized plot generation into separate functions

4. Makefile Structure (40% AI-assisted)

- **Tool Used:** ChatGPT-4
- **Assistance Provided:**

    - Basic Makefile template with variables
    - Dependency management syntax
    - Compilation flags for pthread and math library

- **My Contribution:**
    - Customized for my roll number and file naming convention
    - Added proper cleanup rules
    - Tested compilation on my system
    - Verified linking with `-lm` and `-pthread`

Components Written Independently (100% Original)

1. **Core Program Logic:**
    - Process creation using `fork()` and `wait()` in Program A
    - Thread creation using `pthread_create()` and `pthread_join()` in Program B
    - Command-line argument parsing and validation
    - Worker count override logic for Part D
2. **Analysis and Interpretation:**
    - All observations in this report
    - Performance analysis and comparisons
    - Theoretical explanations (Amdahl's Law, context-switch overhead)
    - Conclusions and insights
3. **Documentation:**
    - README.md structure and content
    - Code comments and documentation
    - This report's written analysis

Understanding Verification

I can explain and defend every line of code in this assignment, including:

- How `fork()` creates child processes and memory duplication
- How `pthread` shares address space between threads
- How `taskset` pins processes to specific CPU cores
- How AWK parses `top` and `iostat` output
- How matplotlib generates visualizations from CSV data
- Trade-offs between processes and threads

Honesty Statement

I certify that:

1. All AI-generated code has been reviewed, understood, and tested by me
2. I can reproduce the results without AI assistance
3. I can explain the logic and rationale during viva examination

4. I have properly disclosed all AI usage as per assignment requirements

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Conclusion

Summary of Findings

This assignment provided hands-on experience comparing **process-based** and **thread-based** parallel programming models across three distinct workload types.

Key Takeaways:

1. **Threads Excel in CPU-Bound Tasks:**
   - 14% faster execution (36.4s vs 42.4s)
   - 3× better CPU utilization (195% vs 67%)
   - Lower context-switch overhead enables better parallelism
2. **Implementation Model Irrelevant for I/O-Bound Tasks:**
   - Both achieve ~1.8s execution time
   - Disk is the bottleneck, not CPU scheduling
   - I/O operations dominate execution time
3. **Optimal Worker Count = Available CPU Cores:**
   - Best performance at 3 workers on 3 cores
   - Beyond 3: exponential performance degradation
   - Threads degrade faster but from higher baseline
4. **Context-Switch Overhead is Real:**
   - Processes: visible in low CPU% (~60-75%)
   - Each process switch involves full state save/restore
   - Threads: lightweight switches enable near-300% CPU saturation
5. **Resource Contention Effects:**
   - 4 workers on 3 cores: ~50% slowdown
   - 8 workers on 3 cores: 3× slowdown
   - Scheduler overhead compounds with oversubscription

Practical Implications

When to Use Processes:

- Need memory isolation for security/stability
- Independent tasks with minimal communication
- Risk of memory corruption requires separation

When to Use Threads:

- CPU-intensive parallel computation
- Shared data structures (reduced memory overhead)
- Frequent inter-worker communication needed

When Neither Matters:

- I/O-bound workloads
- Tasks waiting on external resources (network, disk)
- Single-core systems

Learning Outcomes Achieved

1. ✅ Implemented multi-process and multi-threaded programs in C
2. ✅ Measured system performance using Linux monitoring tools
3. ✅ Automated benchmarking using bash scripting
4. ✅ Analyzed scalability characteristics of parallel programs
5. ✅ Visualized performance data using Python plotting libraries
6. ✅ Understood trade-offs between processes and threads

Future Exploration

Potential extensions to this work:

- Test on systems with 8, 16, 32 cores to see scaling limits
- Implement hybrid model (processes containing multiple threads)
- Measure memory consumption differences
- Analyze cache behavior using `perf` tool
- Compare with other models (async I/O, coroutines)

Appendix

System Specifications

Host System (Hardware)

- **Model:** Macbook Air M4
- **SOC:** Apple M4 (10-core CPU)
- **Memory:** 16 GB Unified Memory (LPDDR5X)
- **Host OS:** macOS Tahoe 26.2

Runtime Environment (Docker)

- **OS Image:** Ubuntu 22.04 LTS
- **Kernel Version:** 6.10.14-linuxkit
- **Virtualization:** Docker Desktop on Apple Silicon

Compilation Commands

```
# Clean previous builds
make clean

# Compile both programs
make

# Expected output:
# gcc -Wall -Wextra -pthread -o Program_A MT25067_Part_A_Program_A.c
MT25067_Part_B_workers.c -lm
# gcc -Wall -Wextra -pthread -o Program_B MT25067_Part_A_Program_B.c
MT25067_Part_B_workers.c -lm
```

Execution Commands

Part C

```
# Run measurement automation
./MT25067_Part_C_shell.sh

# Output: MT25067_Part_C_CSV.csv
```

Part D

```
# Run scalability tests
./MT25067_Part_D_shell.sh

# Output: MT25067_Part_D_CSV.csv
```

Plot Generation

```
# Generate all plots
python3 MT25067_Part_D_plot.py

# Outputs:
# - MT25067_Part_C_Time_Plot.png
# - MT25067_Part_C_CPU_Plot.png
# - MT25067_Part_C_Disk_Plot.png
# - MT25067_Part_D_Scalability_Plot.png
# - MT25067_Part_D_CPU_Trend_Plot.png
```

References

1. **Operating Systems Concepts** (10th Edition) - Silberschatz, Galvin, Gagne

  - Chapter 3: Processes
  - Chapter 4: Threads

2. **Linux Man Pages:**

   - `man fork`
   - `man pthread_create`
   - `man taskset`
   - `man top`
   - `man iostat`

3. **Course Materials:**

   - CSE638 Lecture Slides on Process Management
   - CSE638 Tutorial on Threading

4. **Online Resources:**

   - The Linux Programming Interface - Michael Kerrisk
   - POSIX Threads Programming Guide - Lawrence Livermore National Laboratory

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End of Report