

# Pipeline Program with Producer-Consumer Threads

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## Overview

This document provides a comprehensive analysis of the implementation and performance evaluation of a multithreaded producer-consumer pipeline program. The objective of this assignment is to explore the efficiency of multithreading in data processing and to analyze the performance using the `perf` tool.

## Objectives

- Implement a producer-consumer pipeline using threads.
- Analyze the performance of the program under various configurations.
- Utilize the `perf` tool to gather performance metrics and insights.

## Implementation Details

### Producer-Consumer Model

- **Producer Threads:**
  - Responsible for generating data and placing it into a shared buffer.
  - Example: Each producer thread populates 100 random numbers into a shared array.
  - Utilizes condition variables to signal consumers when new data is available.
- **Consumer Threads:**
  - Retrieve data from the shared buffer and process it.
  - Example: Each consumer thread computes the average of the numbers retrieved from the buffer.
  - Uses mutexes to ensure exclusive access to the shared buffer during data retrieval.

### Synchronization Mechanisms

- **Mutexes:**
  - Used to protect shared resources and prevent race conditions.
- **Condition Variables:**
  - Employed to signal consumer threads when data is available in the buffer, allowing for efficient waiting and notification.

## Performance Analysis

### Metrics Analyzed

- **Execution Time:**
  - Measured the total time taken for the producer-consumer pipeline to complete its operations.
- **Throughput:**

- Calculated as the number of data items processed per second, providing insight into the efficiency of the pipeline.
- **Context Switches:**

- Monitored the number of context switches occurring during execution to evaluate thread management efficiency.

- **Cache Behavior:**

- Analyzed cache hits and misses to understand memory access patterns and their impact on performance.

Consumer 3: Consumed item 52, Running avg: 50.74  
Consumer 3: Finished consuming 100 items, Average: 50.74

Performance Results:  
Execution time: 0.0101 seconds  
Total items processed: 400  
Throughput: 39779.36 items/second

Consumer Results:  
Consumer 0 average: 50.14  
Consumer 1 average: 52.99  
Consumer 2 average: 47.93  
Consumer 3 average: 50.74

Performance counter stats for './bin/producer\_consumer 4 10 100':

CPU Metric	Value	Description
cpu-migrations	79	Number of times the CPU core was migrated.
branch-misses	3,93,398	Number of branch mispredictions.
L1-dcache-loads	73,21,228	Number of L1 data cache loads.
L1-dcache-load-misses	4,27,769	Number of L1 data cache load misses. # 5.84% of all L1-dcache accesses
L1-dcache-stores	<not supported>	Number of L1 data cache stores.
LLC-Loads	<not supported>	Number of LLC (Last Level Cache) loads.
LLC-load-misses	<not supported>	Number of LLC load misses.
LLC-stores	<not supported>	Number of LLC stores.
LLC-prefetches	<not supported>	Number of LLC prefetches.

0.012919499 seconds time elapsed  
0.001045000 seconds user  
0.015838000 seconds sys

```

Consumer 2: Finished consuming 100 items, Average: 49.89
Consumer 3: Finished consuming 100 items, Average: 54.30

Performance Results:
  Execution time:      0.0235 seconds
  Total items processed: 400
  Throughput:          17056.84 items/second

Consumer Results:
  Consumer 0 average: 49.25
  Consumer 1 average: 47.28
  Consumer 2 average: 49.89
  Consumer 3 average: 54.30

Performance counter stats for './bin/producer_consumer 4 10 100':

  22.94 msec task-clock          #   0.879 CPUs utilized
    661    context-switches       #   28.811 K/sec
     86    cpu-migrations        #   3.748 K/sec
     81    page-faults           #   3.531 K/sec
 3,27,80,261    cycles           #   1.429 GHz          (18.91%)
 14,96,834    stalled-cycles-frontend #   4.57% frontend cycles idle  (57.83%)
 30,29,261    stalled-cycles-backend  #   9.24% backend cycles idle  (80.38%)
 1,69,14,412    instructions      #   0.52 insns per cycle
                                #   0.18 stalled cycles per insn  (93.53%)
 42,17,934    branches          # 183.847 M/sec
   4,44,540    branch-misses     # 10.54% of all branches  (97.32%)
 77,26,369    L1-dcache-loads   # 336.769 M/sec          (59.96%)
 4,47,288    L1-dcache-load-misses # 5.79% of all L1-dcache accesses  (37.39%)
<not supported>    LLC-loads
<not supported>    LLC-load-misses

 0.026092981 seconds time elapsed

 0.002912000 seconds user
 0.018551000 seconds sys

```

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Consumer 2: Finished consuming 100 items, Average: 56.45
Consumer 3: Finished consuming 100 items, Average: 47.82

Performance Results:
  Execution time:      0.0165 seconds
  Total items processed: 400
  Throughput:          24273.87 items/second

Consumer Results:
  Consumer 0 average: 52.27
  Consumer 1 average: 49.48
  Consumer 2 average: 56.45
  Consumer 3 average: 47.82

Performance counter stats for './bin/producer_consumer 4 10 100':

  19.84 msec task-clock          #   1.048 CPUs utilized
  4,41,36,463    cycles           #   2.224 GHz          (56.01%)
  1,58,37,691    instructions    #   0.36 insns per cycle  (67.76%)
  19,23,764    cache-references #   96.952 M/sec          (93.11%)
   4,61,665    cache-misses     # 24.00% of all cache refs  (91.40%)
  37,27,526    branches          # 187.856 M/sec          (98.29%)
  3,92,333    branch-misses    # 10.53% of all branches  (96.47%)
   428    context-switches     # 21.570 K/sec
    62    cpu-migrations      #   3.125 K/sec

 0.018932147 seconds time elapsed

 0.001667000 seconds user
 0.015617000 seconds sys

```

## Tools Used

- **perf Tool:**
  - Utilized for profiling the program and gathering detailed performance metrics.
  - Key metrics analyzed include CPU usage, memory bandwidth, cache references, cache misses, and I/O wait time.

## Results

### Execution Time

- The execution time was recorded for various configurations of producer and consumer threads. The results indicated that optimal performance was achieved with a specific number of threads.

## Throughput

- The throughput was measured and plotted against the number of threads. The results showed a clear trend of increasing throughput with the number of threads, up to a certain point.

## Context Switches

- The number of context switches was recorded, revealing that excessive context switching negatively impacted performance as the number of threads increased.

## Cache Behavior

- Cache metrics were analyzed, showing a correlation between cache hits and overall execution time. Programs with better cache performance exhibited lower execution times.

Samples: 208 of event 'cycles:P', Event count (approx.): 49128992				
Children	Self	Command	Shared Object	Symbol
+ 51.05%	0.00%	producer_consum	libc.so.6	[.] __vfprintf_internal
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] __printf_buffer_to_file_done
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] __printf_buffer_flush_to_file
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] _IO_file_xsputn@@GLIBC_2.2.5
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] _IO_do_write@@GLIBC_2.2.5
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] new_do_write
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] _IO_file_write@@GLIBC_2.2.5
+ 48.94%	0.00%	producer_consum	libc.so.6	[.] __GI___libc_write
+ 46.08%	0.00%	producer_consum	producer_consumer	[.] consumerFunction
+ 44.12%	0.00%	producer_consum	[kernel.kallsyms]	[k] ksys_write
+ 44.12%	3.08%	producer_consum	[kernel.kallsyms]	[k] vfs_write
+ 38.11%	0.00%	producer_consum	[kernel.kallsyms]	[k] file_tty_write.isra.0
+ 36.80%	8.51%	producer_consum	[kernel.kallsyms]	[k] n_tty_write
+ 30.43%	1.53%	producer_consum	[kernel.kallsyms]	[k] __schedule
+ 28.51%	2.72%	producer_consum	producer_consumer	[.] producerFunction
+ 26.89%	0.00%	producer_consum	[kernel.kallsyms]	[k] schedule
+ 26.87%	0.00%	producer_consum	[kernel.kallsyms]	[k] __x64_sys_futex
+ 26.12%	0.00%	producer_consum	[unknown]	[k] 0x000000003070e890
+ 25.75%	0.00%	producer_consum	[kernel.kallsyms]	[k] do_futex
+ 21.54%	0.31%	producer_consum	[kernel.kallsyms]	[k] futex_wait
+ 21.23%	0.00%	producer_consum	[kernel.kallsyms]	[k] __futex_wait
+ 20.90%	0.00%	producer_consum	[kernel.kallsyms]	[k] futex_wait_queue
+ 19.57%	0.00%	producer_consum	[unknown]	[k] 0x000000003070f1f0
+ 18.57%	0.00%	producer_consum	[unknown]	[k] 0x000000003070eed0
+ 18.40%	0.00%	producer_consum	[kernel.kallsyms]	[k] pty_write
+ 18.40%	1.86%	producer_consum	[kernel.kallsyms]	[k] tty_insert_flip_string_and_push_buffer
+ 18.21%	0.00%	producer_consum	libc.so.6	[.] __lll_lock_wait_private
+ 16.54%	3.08%	producer_consum	[kernel.kallsyms]	[k] queue_work_on
+ 10.33%	0.00%	producer_consum	[unknown]	[k] 0x000000003070ebb0
+ 9.29%	1.55%	producer_consum	[kernel.kallsyms]	[k] try_to_wake_up
+ 7.89%	0.00%	producer_consum	[kernel.kallsyms]	[k] syscall_exit_to_user_mode
+ 7.72%	0.64%	producer_consum	[kernel.kallsyms]	[k] common_interrupt
+ 7.72%	0.00%	producer_consum	[kernel.kallsyms]	[k] asm_common_interrupt
+ 7.72%	0.00%	producer_consum	[kernel.kallsyms]	[k] __irq_exit_rcu
+ 7.72%	0.00%	producer_consum	[kernel.kallsyms]	[k] handle_softirqs
+ 7.72%	0.00%	producer_consum	[kernel.kallsyms]	[k] net_rx_action
+ 7.72%	0.00%	producer_consum	[kernel.kallsyms]	[k] __napi_poll
+ 7.72%	0.00%	producer_consum	[ath10k_pci]	[k] ath10k_pci_napi_poll
+ 7.38%	1.16%	producer_consum	[kernel.kallsyms]	[k] __queue_work.part.0
+ 7.35%	0.00%	producer_consum	[unknown]	[k] 0x0000000100000000
+ 6.82%	0.00%	producer_consum	[kernel.kallsyms]	[k] __pick_next_task
+ 6.82%	0.00%	producer_consum	[kernel.kallsyms]	[k] pick_next_task_fair
+ 6.69%	0.00%	producer_consum	producer_consumer	[.] bufferGet
+ 6.56%	0.00%	producer_consum	libc.so.6	[.] __futex_abstimed_wait_common
+ 6.36%	1.31%	producer_consum	[kernel.kallsyms]	[k] finish_task_switch.isra.0
+ 6.27%	1.26%	producer_consum	[kernel.kallsyms]	[k] dequeue_entities

Press '?' for help on key bindings

```
technogenius ⌘ ➜ /run/media/technogenius/Practice/MTech_IIITD/Semester 2/Graduate System/Assignment_02_P2
↳ perf record -g ./bin/producer_consumer 4 10 100
Running producer-consumer test with:
  Thread pairs:        4
  Buffer size:        10
  Items per producer: 100
  Total items:       400

Producer 0: Produced item 80
Producer 0: Produced item 2
Producer 0: Produced item 53
Producer 0: Produced item 98
Producer 0: Produced item 28
Producer 0: Produced item 58
Producer 0: Produced item 2
Producer 0: Produced item 98
Producer 0: Produced item 62
Producer 0: Produced item 93
Producer 1: Produced item 48
Producer 1: Produced item 52
Producer 1: Produced item 7
Producer 1: Produced item 46
Producer 1: Produced item 93
Producer 1: Produced item 52
Producer 1: Produced item 50
Producer 1: Produced item 88
Producer 1: Produced item 25
Producer 1: Produced item 20
Consumer 1: Consumed item 48, Running avg: 48.00
Consumer 1: Consumed item 52, Running avg: 50.00
Consumer 1: Consumed item 7, Running avg: 35.67
Consumer 0: Consumed item 80, Running avg: 80.00
Consumer 0: Consumed item 2, Running avg: 41.00
Consumer 0: Consumed item 53, Running avg: 45.00
Consumer 0: Consumed item 98, Running avg: 58.25
Consumer 0: Consumed item 28, Running avg: 52.20
Consumer 0: Consumed item 58, Running avg: 53.17
Consumer 0: Consumed item 2, Running avg: 45.86
Consumer 0: Consumed item 98, Running avg: 52.38
Consumer 0: Consumed item 62, Running avg: 53.44
Consumer 0: Consumed item 93, Running avg: 57.40
Consumer 0: Consumed item 3, Running avg: 52.45
Producer 2: Produced item 37
Producer 2: Produced item 20
Producer 2: Produced item 89
Producer 2: Produced item 72
Producer 2: Produced item 94
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Producer 0: Produced item 3
Consumer 1: Consumed item 46, Running avg: 38.25
Consumer 1: Consumed item 93, Running avg: 49.20
Consumer 2: Consumed item 37, Running avg: 37.00
Consumer 1: Consumed item 52, Running avg: 49.67
Consumer 1: Consumed item 58, Running avg: 49.71
Producer 3: Produced item 47
Consumer 1: Consumed item 88, Running avg: 54.50
Consumer 1: Consumed item 25, Running avg: 51.22
Consumer 1: Consumed item 20, Running avg: 48.10
Producer 1: Produced item 84
Consumer 1: Consumed item 84, Running avg: 51.36
Producer 0: Produced item 62
Producer 0: Produced item 59
Producer 0: Produced item 100
Producer 0: Produced item 90
Producer 0: Produced item 13
Producer 1: Produced item 98
Producer 0: Produced item 99
Producer 0: Produced item 93
Producer 0: Produced item 20
Producer 0: Produced item 44
Producer 0: Produced item 37
Consumer 2: Consumed item 20, Running avg: 28.50
Producer 1: Produced item 46
Producer 1: Produced item 25
Producer 1: Produced item 95
Producer 1: Produced item 65
Producer 1: Produced item 8
Producer 0: Produced item 71
Consumer 3: Consumed item 87, Running avg: 67.00
Consumer 1: Consumed item 98, Running avg: 55.25
Consumer 1: Consumed item 46, Running avg: 54.54
Consumer 1: Consumed item 25, Running avg: 52.43
Consumer 1: Consumed item 95, Running avg: 55.27
Consumer 1: Consumed item 65, Running avg: 55.88
Consumer 1: Consumed item 8, Running avg: 53.06
Consumer 1: Consumed item 41, Running avg: 52.39
Consumer 0: Consumed item 62, Running avg: 53.25
Consumer 0: Consumed item 59, Running avg: 53.69
Consumer 0: Consumed item 100, Running avg: 57.00
Consumer 0: Consumed item 90, Running avg: 59.20
Consumer 0: Consumed item 13, Running avg: 56.31
Consumer 0: Consumed item 99, Running avg: 58.82
Consumer 0: Consumed item 93, Running avg: 60.72
Consumer 0: Consumed item 20, Running avg: 58.58
Consumer 0: Consumed item 44, Running avg: 57.85
Consumer 0: Consumed item 37, Running avg: 56.86
Consumer 0: Consumed item 71, Running avg: 57.50
```

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Consumer 1: Consumed item 34, Running avg: 44.59
Consumer 1: Finished consuming 100 items, Average: 44.59
Consumer 2: Finished consuming 100 items, Average: 52.37
Consumer 3: Consumed item 39, Running avg: 44.41
Consumer 3: Consumed item 88, Running avg: 44.95
Consumer 3: Consumed item 39, Running avg: 44.88
Consumer 3: Consumed item 92, Running avg: 45.45
Consumer 3: Consumed item 30, Running avg: 45.26
Consumer 3: Consumed item 7, Running avg: 44.81
Consumer 3: Consumed item 72, Running avg: 45.13
Consumer 3: Consumed item 31, Running avg: 44.97
Consumer 3: Consumed item 49, Running avg: 45.01
Consumer 3: Consumed item 61, Running avg: 45.19
Consumer 3: Consumed item 79, Running avg: 45.57
Consumer 3: Consumed item 41, Running avg: 45.52
Producer 3: Produced item 41
Producer 3: Produced item 62
Producer 3: Produced item 16
Producer 3: Produced item 74
Producer 3: Produced item 52
Producer 3: Produced item 7
Producer 3: Produced item 3
Producer 3: Produced item 58
Producer 3: Produced item 30
Producer 3: Produced item 85
Producer 3: Finished producing 100 items
Consumer 3: Consumed item 62, Running avg: 45.70
Consumer 3: Consumed item 16, Running avg: 45.38
Consumer 3: Consumed item 74, Running avg: 45.68
Consumer 3: Consumed item 52, Running avg: 45.75
Consumer 3: Consumed item 7, Running avg: 45.34
Consumer 3: Consumed item 3, Running avg: 44.91
Consumer 3: Consumed item 58, Running avg: 45.04
Consumer 3: Consumed item 30, Running avg: 44.89
Consumer 3: Consumed item 85, Running avg: 45.29
Consumer 3: Finished consuming 100 items, Average: 45.29

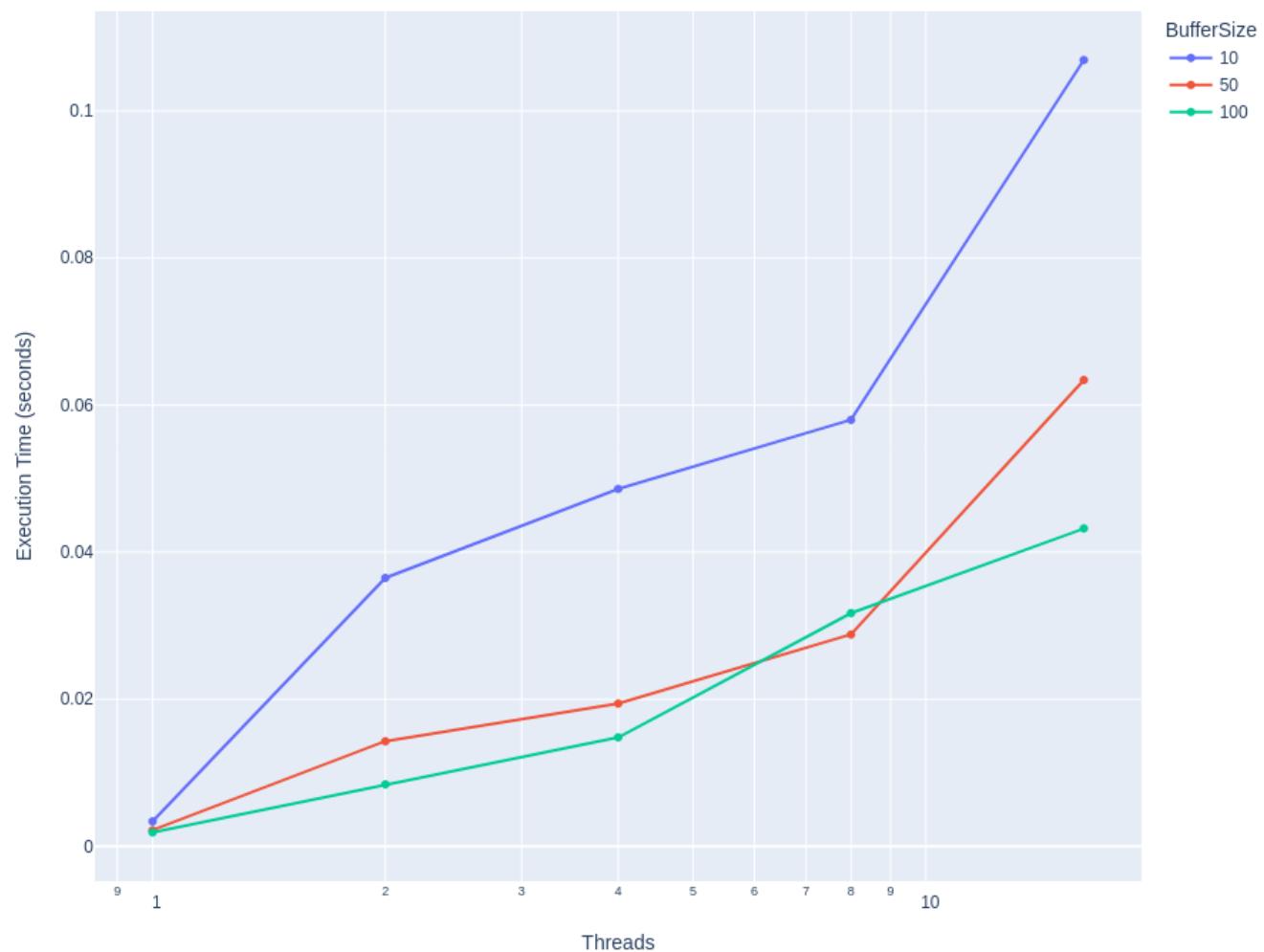
Performance Results:
Execution time:      0.0218 seconds
Total items processed: 400
Throughput:          18362.12 items/second

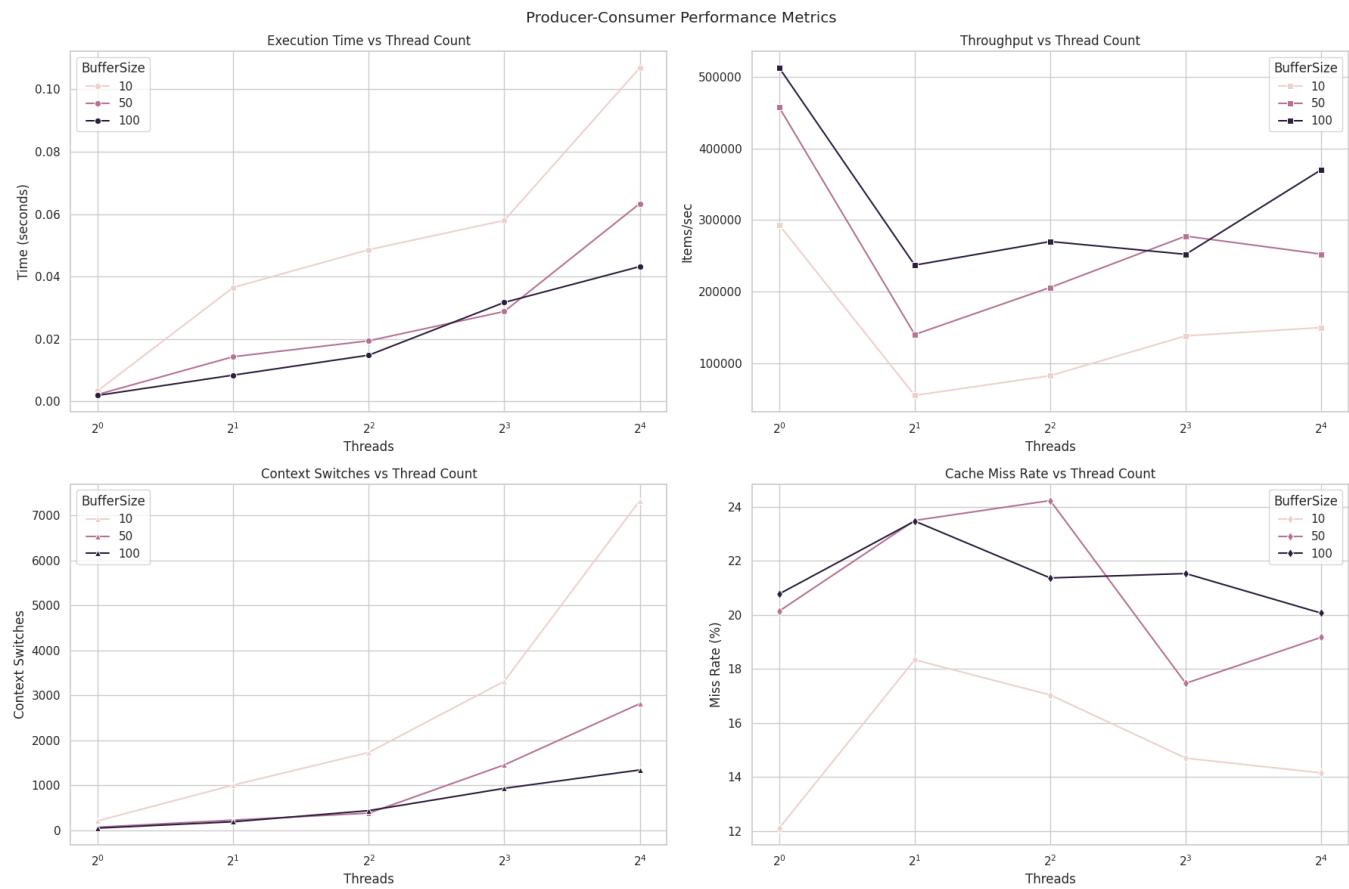
Consumer Results:
Consumer 0 average: 53.95
Consumer 1 average: 44.59
Consumer 2 average: 52.37
Consumer 3 average: 45.29
[ perf record: Woken up 1 times to write data ]
[ perf record: Captured and wrote 0.062 MB perf.data (208 samples) ]
```

## Graphs and Visualizations

- Graphs illustrating the performance metrics (execution time, throughput, context switches) were generated using the `matplotlib` library.
- Comparative analysis of different configurations was visualized, highlighting the optimal number of threads for maximum throughput.

## Interactive Execution Time Analysis





## Observations

- The performance of the producer-consumer pipeline improved with an optimal number of threads, demonstrating the benefits of multithreading.
- Beyond a certain threshold, increasing the number of threads led to diminishing returns due to increased context switching and contention for shared resources.
- The analysis identified potential bottlenecks in the synchronization mechanisms, suggesting areas for future optimization.

## Conclusion

The implementation of the producer-consumer pipeline program successfully demonstrated the advantages of multithreading in data processing. The performance analysis using the `perf` tool provided valuable insights into the program's behavior under different configurations, allowing for the identification of optimization opportunities.