

FACULDADE DE ENGENHARIA DA
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COMPUTAÇÃO PARALELA E DISTRIBUÍDA

CPD Project 1 - Performance evaluation

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1 Problem Description

This project goal is to analyse the impact of memory hierarchy on processor performance during matrix multiplication. We aim to understand how data access patterns influence computational efficiency through various implementations and performance measurements across different input sizes.

2 Algorithms

In order to understand the influence of different algorithms on processor performance during matrix multiplication, we implemented three algorithms that vary primarily in their memory access patterns. To analyze the impact of the programming languages on the performance we implemented the algorithms in **C++** and **Rust**. This choice allows us to compare the efficiency of a compiled, system-level language - **C++** - with a compiled language known for its memory safety and performance focus - **Rust**. Both languages offer high levels of control over memory management, making them suitable for investigating how memory access patterns affect performance.

- **Basic matrix multiplication algorithm** - implemented in C++ and Rust
- **Line matrix multiplication algorithm** - implemented in C++ and Rust
- **Block matrix multiplication algorithm** - implemented in C++

2.1 Basic matrix multiplication algorithm

This algorithm implements a basic matrix multiplication approach, where each element in the resulting matrix is computed by multiplying one row of the first matrix by one column of the second. As a result, the algorithm demonstrates a computational time complexity of $O(n^3)$ and a space complexity of $O(n^2)$, owing to its composition of three nested loops. Here, n represents the size of the input matrices.

The resulting matrix can be calculated using the following equation:

$$C[i][j] = \sum_{k=0}^{n-1} A[i][k] \cdot B[k][j] \quad (1)$$

where C is the resulting matrix, A and B are the input matrices, and n is the size of the matrices.

2.2 Line matrix multiplication algorithm

Instead of directly multiplying a row of the first matrix with a column of the second, this algorithm computes the product of a row of the first matrix with each row of the second. This adjustment results in accessing matrix elements in a cache-friendly row-major order, reducing cache misses and improving execution time, particularly for large matrices. Despite maintaining the same time and space complexity as the algorithm before, this algorithm's efficient cache usage often makes it faster than the basic matrix multiplication algorithm in practical scenarios.

2.3 Block matrix multiplication algorithm

The Block Matrix Multiplication algorithm is designed to further optimize memory access patterns by dividing the matrices into smaller blocks. This strategy enhances cache utilization and reduces cache misses compared to the Line Matrix Multiplication approach. The algorithm operates by multiplying submatrices within these blocks, thereby minimizing the distance between accessed elements and exploiting spatial locality. Although sharing identical space and time complexities with the preceding algorithms, block matrix multiplication excels in performance, particularly with large matrices. This superiority derives from its capability to partition matrices into smaller blocks, effectively decreasing the incidence of cache misses.

3 Performance Metrics

To assess the performance of the C++ implementations, we utilized the PAPI (Performance API), providing us with comprehensive hardware performance monitoring. Our evaluation comprised the following key metrics:

- **Execution Time** - This metric quantifies the duration taken by the program to complete its execution. It serves as a fundamental benchmark for computing overall performance and facilitating comparative analysis.
- **L1 and L2 Cache Misses** - These metrics quantify the number of cache misses occurring in the L1 and L2 caches, respectively. A cache miss arises when the requested data is not found in the cache and require retrieval from main memory. This metric provides valuable insights into the memory access patterns of the program, as frequent cache misses can lead to increased execution times, which means that minimizing cache misses is crucial for optimizing program performance!
- **MFlops** - This metric, derived from "Million Floating-point Operations per Second", provides a measure of a computer's performance in executing floating-point arithmetic operations. It quantifies the rate at which a system can perform such operations and is calculated using the following formula:

$$MFlops = \frac{\text{Number of Floating Point Operations}}{\text{Execution Time in Seconds}} \times 10^{-6} \quad (2)$$

3.1 Hardware used

4 Results and Analysis

5 Conclusion