

# AMS 562 Homework #5

## Multithreading with C++ Threads and OpenMP

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Due: December 1, 2025, 11:59 PM EST

### 1 Objective

The objective of this assignment is to gain practical experience with multithreading in C++ using both built-in threading libraries and OpenMP, while also gaining exposure to CMake and Google Test frameworks for building and testing C++ projects. By completing this assignment, you will:

- Implement multithreaded programs using C++ threads, futures, and OpenMP.
- Understand and compare different parallel programming models.
- Use CMake and Google Test frameworks for building and testing C++ projects.
- Analyze and report on the performance of multithreaded applications.

### 2 Description

In this assignment, you will explore multithreading in C++ by implementing two fundamental parallel algorithms: the inner product and the inclusive scan.

#### 2.1 Inner Product

The **inner product**, also known as the dot product, is a fundamental operation in many scientific computing applications. Given two vectors  $\mathbf{a} = [a_1, a_2, \dots, a_n]$  and  $\mathbf{b} = [b_1, b_2, \dots, b_n]$ , their inner product is defined as:

$$\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^n a_i b_i$$

Computing the inner product efficiently is crucial in various applications such as machine learning, physics simulations, and numerical methods.

In this part, you will implement a parallel version of the inner product using OpenMP directives to improve performance on multi-core processors.

##### 2.1.1 Provided Implementation

A detailed implementation of the inner product using C++ threads and futures is provided in the file `inner_product_threads.hpp`. This implementation divides the vectors into chunks and computes partial sums in parallel threads.

### 2.1.2 Your Task

Your task is to implement the function `parallel_inner_product_openmp` using OpenMP directives. Pay close attention to the TODO items in the following files to guide your implementation:

- `inner_product_openmp.hpp`
- `test_inner_product.cpp`

You may use `#pragma omp taskloop` and `#pragma omp parallel for` to achieve a task-based style similar to using threads and gain finer control compared to using only `#pragma omp parallel for`. Also update the testing blocks in the `test_inner_product.cpp` file in the `tests` subdirectory to test your implementation.

## 2.2 Inclusive Scan

The **inclusive scan**, also known as the prefix sum, is an operation that computes all the partial sums of a sequence. Given an input sequence  $[x_1, x_2, \dots, x_n]$ , the inclusive scan produces an output sequence  $[y_1, y_2, \dots, y_n]$  where:

$$y_i = \sum_{k=1}^i x_k \quad \text{for } i = 1, 2, \dots, n$$

The inclusive scan is an important building block in parallel algorithms and is used in applications such as data analysis, computational geometry, and parallel sorting algorithms.

C++17 introduced the `std::inclusive_scan` function in the Standard Library, which provides a sequential implementation of the inclusive scan. In this assignment, you will implement a parallel version of the inclusive scan using C++ threads and futures.

### 2.2.1 Provided Implementation

A detailed implementation of the inclusive scan using OpenMP is provided in the file `inclusive_scan_openmp.hpp`. This implementation uses OpenMP tasks to perform the scan operation in parallel.

### 2.2.2 Your Task

Your task is to implement the function `parallel_inclusive_scan_threads` using C++ threads and futures. Refer to the TODO items in the following files to assist your implementation:

- `inclusive_scan_threads.hpp`
- `test_inclusive_scan.cpp`

Ensure you follow the instructions within the TODO comments to correctly divide the input, manage threads, and combine partial results. Also update the testing blocks in the `test_inclusive_scan.cpp` file in the `tests` subdirectory to verify your implementation.

## 2.3 Performance Comparison and Reporting

After implementing both functions, you will:

- Run the provided tests using Google Test to verify the correctness of your implementations.
- Measure the performance of your implementations and compare them with the provided ones.
- Analyze the scalability and efficiency of your code with different input sizes and numbers of threads.
- Document your findings in a report.

## 3 Submission Guidelines

### 3.1 GitHub Repository

#### 1. Create a Private Repository:

- Sign in to your GitHub account and create a private repository named `AMS562_Homework5`.

#### 2. Push Your Code:

- Include all C++ source (`.cpp`) files, header (`.hpp`) files, CMake files, and test scripts.
- Organize your project with the following structure:

```
project_root/  
|-- src/  
    |-- inner_product_threads.hpp  
    |-- inner_product_openmp.hpp  
    |-- inclusive_scan_threads.hpp  
    |-- inclusive_scan_openmp.hpp  
|-- tests/  
    |-- test_inner_product.cpp  
    |-- test_inclusive_scan.cpp  
|-- CMakeLists.txt  
|-- cmake/  
    |-- openmp_config.cmake  
    |-- gtest_config.cmake  
|-- README.md
```

- Note that you can implement everything directly in the header files using templates.
- Please follow the detailed instructions in the `README.md` for the following:
  - **Project Overview:** A brief description of the project and its objectives.
  - **Build Instructions:** Step-by-step guide on how to build the project using CMake.
  - **Test Instructions:** How to run the tests using Google Test.

#### 3. Share the Repository:

- Add the TA (`yuxuanye1`) as a collaborator to your private repository.
- Ensure that your last commit is made before the project deadline.

### 3.2 Code Documentation

- **Commenting:**

- Use comments to explain your code where necessary.

- **Code Quality:**

- Follow consistent coding standards and naming conventions.
  - Ensure proper indentation and code formatting for readability.

### 3.3 Report Submission

#### 1. Report Document:

- Create a 2–3 page report.
- Format the report with Times New Roman, font size 12, single line spacing, and 1-inch margins.

## 2. Report Content:

- **Repository URL:** Include the URL of your GitHub repository.
- **Implementation Details:** Describe your approach to implementing the functions.
- **Testing and Verification:** Summarize how you tested your code and the results.
- **Performance Analysis:** Present your performance measurements and analysis.
- **Challenges and Lessons Learned:** Reflect on any difficulties faced and what you learned.

3. **Submission:** Upload the report as a PDF to Brightspace before the deadline.

## 3.4 Deadlines

- **Project Deadline:** December 1st, 2025, by 11:59 PM EST.

## 4 Grading Rubric

- **Code Implementation (40%):**
  - Correctness, functionality, and efficiency of your code.
- **Performance Analysis (20%):**
  - Quality of performance measurements, comparisons, and analysis.
- **Testing (20%):**
  - Use of Google Test, test coverage, and effectiveness.
- **Documentation and Report (10%):**
  - Clarity, completeness, and quality of the report.
- **Code Quality and Organization (10%):**
  - Code structure, readability, and use of CMake.