

# CS542200 Parallel Programming

## Homework 2: Mandelbrot Set

Due: Sun Nov 2, 2025 23:59

### 1 GOAL

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In this assignment, you are asked to parallelize the sequential *Mandelbrot Set* program, and learn the following skills:

- Get familiar with thread programming using Pthread and OpenMP.
- Combine process and thread to implement a hybrid parallelism solution .
- Understand the importance of load balance.

### 2 PROBLEM DESCRIPTION

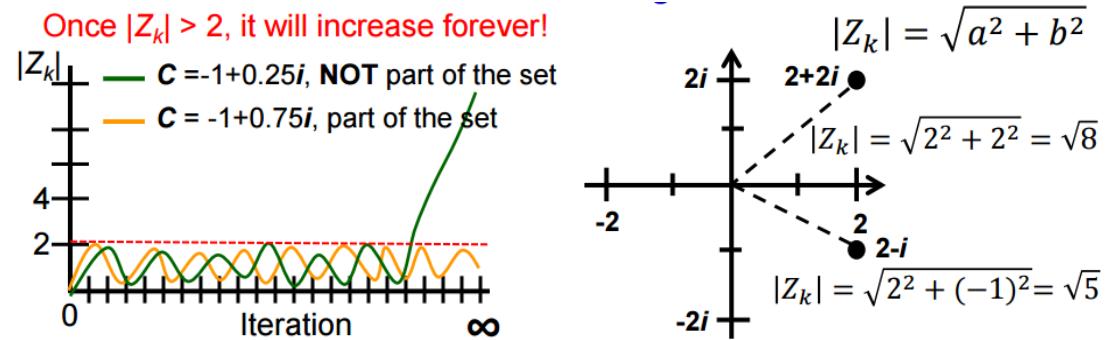
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The *Mandelbrot Set* is a set of complex numbers that are quasi-stable when computed by iterating the function:

$$Z_k = C, \quad k = 0$$

$$Z_k = Z_{k-1}^2 + C, \quad k \geq 1$$

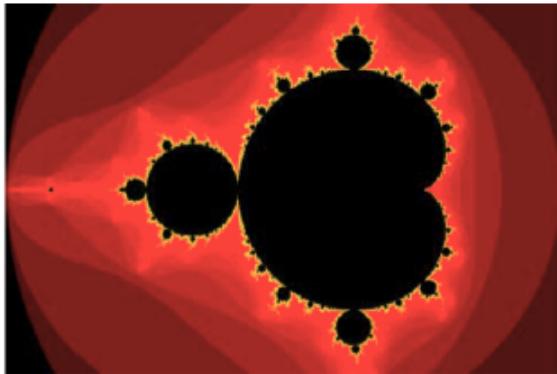
- $C$  is some complex number:  $C = a + bi$
- $Z_k$  is the  $k^{th}$  iteration of the complex number
- if  $|Z_k| \leq 2$  for any  $k$ ,  $C$  belongs to the *Mandelbrot Set*



What exact is the *Mandelbrot Set*?

- It is fractal: An object that display self-similarity at various scale; magnifying a fractal reveals small-scale details similar to the larger-scale characteristics

- After plotting the *Mandelbrot Set* determined by thousands of iterations:



For more information, please refer to lecture notes.

## 3 INPUT / OUTPUT FORMAT

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### 3.1 Input specification

The input parameters are specified from the command line. There are no input files.

Your programs should accept the following `srun` command:

```
srun -n $procs -c $t ./exe $out $iter $x0 $x1 $y0 $y1 $w $h
```

For example, the image in Sec.2 is created by:

```
srun -n1 -c1 ./hw2seq out.png 10000 -2 2 -2 2 800 800
```

The meanings of the arguments are:

- `$procs` – int; [1, 48]; number of processes. Always 1 for the Pthread version.
- `$t` – int; [1, 12]; number of threads per process. (technically, this is the number of CPUs you can use per process; you are allowed to use more or fewer threads)
- `$out` – string; the path to the output file.
- `$iter` – int; [1,  $2 \times 10^8$ ]; number of iterations. (the largest int is around  $2.1 \times 10^9$ )
- `$x0` – double; [-10, 10]; inclusive bound of the real axis.
- `$x1` – double; [-10, 10]; non-inclusive bound of the real axis.
- `$y0` – double; [-10, 10]; inclusive bound of the imaginary axis.
- `$y1` – double; [-10, 10]; non-inclusive bound of the imaginary axis.
- `$w` – int; [1, 16000]; number of points in the x-axis for output.
- `$h` – int; [1, 16000]; number of points in the y-axis for output.

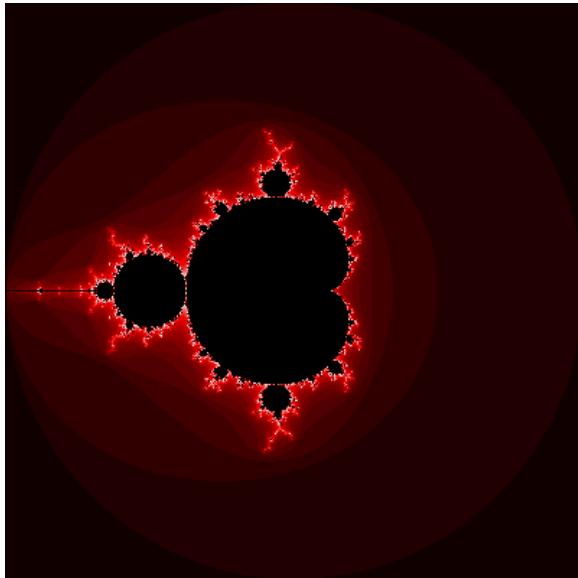
### 3.2 Output specification

Your programs should produce a **PNG image** at `$out`, visualizing the *Mandelbrot Set* in the given range.

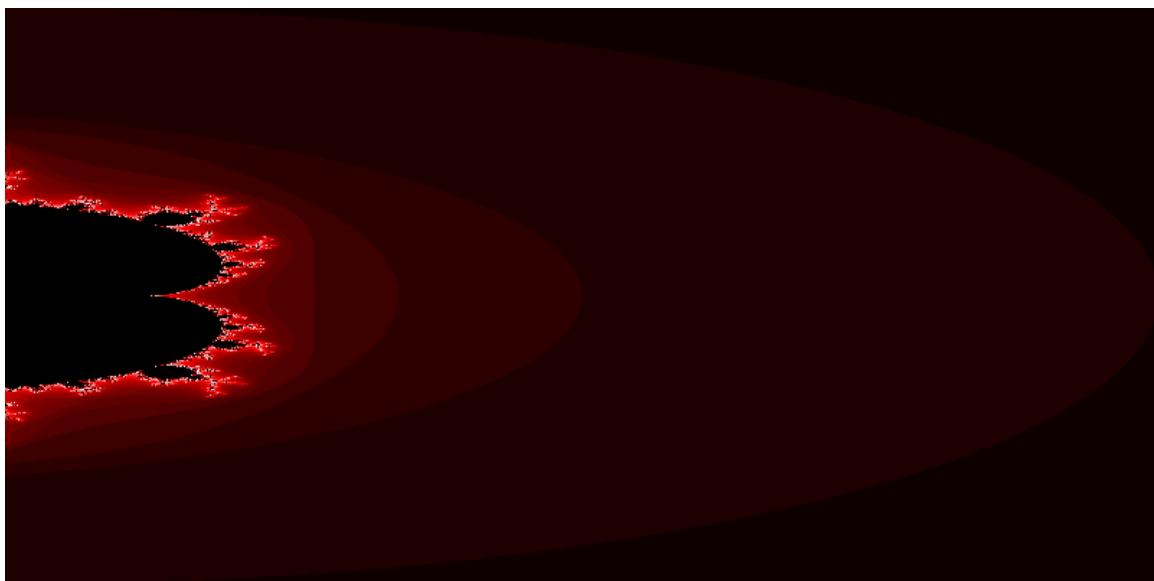
We provide a sequential version to show how the pixels are rendered.

Example 1: `srun ./exe $out $iter -2 2 -2 2 400 400`

x axis:[-2 2), 400 pints = {-2, -1.99, -1.98, ... 1.98, 1.99}



Example 2: `srun ./exe $out $iter 0 2 -2 2 800 400`



## 4 WORKING ITEMS

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In this assignment, you are asked to parallelize the sequential *Mandelbrot Set* program by implementing the following two versions:

1. `pthread`: Single node shared memory programming using Pthread
2. `hybrid`: Single node hybrid parallelism programming using MPI + OpenMP
  - MPI are used to balance tasks among processes, and OpenMP threads are used to perform computations.
  - Pthread library could also be used to create additional threads for communications.

### Requirements:

- **Must follow the input/output file format and execution command line arguments specifications described in Section 3.**
- **No mathematical optimization is permitted.** That means the computations must be performed on each and every pixel.

## 5 REPORT

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Your report must contain the following contents, and you can add more as you like.

### 1. Title, name, student ID

### 2. Implementation

Explain your implementations, especially in the following aspects:

- ✓ How you implement each of requested versions, especially for the hybrid parallelism.
- ✓ How do you partition the task?
- ✓ What technique do you use to reduce execution time and increase scalability?
- ✓ Other efforts you made in your program

### 3. Experiment & Analysis

Explain how and why you do these experiments? Explain how you collect those measurements? Show the result of your experiments in plots, and explain your observations.

#### i. Methodology

(a). **System Spec** (If you run your experiments on your own machine)

Please specify the system spec by providing the CPU, RAM, storage and network (Ethernet / InfiniBand) information of the system.

(b). **Performance Metrics**

How do you measure computing time of your programs? How do you compute the values in the plots?

**ii. Plots: Scalability & Load Balancing & Profile**

- Experimental Method:
  - **Test Case Description:** Explain the test data and its sizes you've chosen.
  - **Parallel Configurations:** Describe the number of processes and threads used, and how cores are distributed.
- Performance Measurement:
  - Use a profiler for performance analysis.
  - Provide basic metrics like execution time.
- Analysis of Results:
  - Display results generated by the profiler; this could be in the form of tables, charts, or other visualization tools.
  - **Conduct strong scalability experiments**, and plot the speedup and time profile results.
  - **Show how balanced it is** in each of your experiments by plots..
- Optimization Strategies:
  - Based on the analysis results, propose potential optimization strategies.
  - If optimizations have been implemented, provide a comparison of performance before and after the enhancements.
- The plot must contain at least 4 different scales (number of processes, threads).
- **Make sure your plots are properly labeled and formatted.**
- You are recommended to choose a proper problem size to ensure the experiment results are accurate and meaningful.

**iii. Discussion** (must base on the results in the plots)

- (a). Compare and discuss the **scalability** of your implementations.
- (b). Compare and discuss the **load balance** of your implementations.

**iv. Others**

- You are strongly encouraged to conduct more experiments and analysis of your implementations.

#### 4. Experience & Conclusion

- ✓ Your conclusion of this assignment.
- ✓ What have you learned from this assignment?
- ✓ What difficulties did you encounter in this assignment?
- ✓ If you have any feedback, please write it here. Such as comments for improving the spec of this assignment, etc.

## 6 GRADING

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### 1. [45%] Correctness (pthread version: 15%, hybrid version: 30%)

- We will use several test cases to test your implementations. You will get full points for an implementation if you pass all the test cases, no points for it otherwise.
- For each test case, your implementation will be considered correct if:
  - ❖ Your implementation produced a valid PNG image.
  - ❖ At least **99.8%** of the pixels in your output image are identical to the corresponding pixel produced by the sequential version.
  - ❖ You can use **hw2-diff** to check the difference between two png images. e.g. **hw2-diff slow01.png myout.png**
  - ❖ The **execution time** of your implementation is **shorter** than:
    - the execution time of the sequential version + 30 seconds

### 2. [15%] Performance (pthread version: 5%, hybrid version: 10%)

- We will use several different test cases (denoted  $C$ ) to run your code.
- Your performance score will be given by:

$$\sum S(C) \times \frac{T_{best}(C)}{T_{yours}(C)}$$

- ❖  $C$  is a test case: the set of input parameters excluding parallelism settings. e.g. `$x0, $x1, $y0, $y1, $w, $h`.
- ❖  $S(C)$  is the score allocated to the test case.
- ❖  $T_{best}(C)$  is the shortest execution time of all students for the test case, excluding incorrect implementations.

- ❖  $T_{yours}(C)$  is your shortest execution time of {pthread, hybrid} for the test case, excluding incorrect implementations.
- ❖  $\sum S(C) = 15$

### 3. [30%] Report

- Grading is based on your evaluation, discussion and writing. If you want to get more points, design or conduct more experiments to analyze your implementation.

### 4. [10%] Demo

- i、 Explain your implementations.
- ii、 Explain the key results and findings from your report.
- iii、 (Optional) Your extra efforts. (Why do you deserve a higher score?)

### 5. Policy

- i、 **0 points will be given to the cheater** (even copying code from the Internet).
- ii、 **No late submissions after the deadline will be accepted.**

## 7 SUBMISSION & REMINDER

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Upload these files to `eeclass` with **NO compression** before the deadline

- `hw2a.cc` (pthread version)
- `hw2b.cc` (hybrid version)
- `Makefile` (optional)
- `hw2_{student_ID}.pdf`

Note:

1. Deadline: **November 2, 2025 23:59.**
2. Refer to `/home/pp25/share/hw2` on Origo Apollo platform for the sequential version of *Mandelbrot Set*, Makefile and test cases.

3. Your Makefile must be able to build the corresponding targets of the implementations: `pthread`, `hybrid`. If you're unsure how to write a Makefile, you can use the provided example Makefile as-is.
4. **Self-checking scripts** are provided to verify the correctness of your code. Type the following commands under your source code directory for testing: `hw2a-judge` for pthread version, `hw2b-judge` for hybrid version.
5. **A scoreboard system** will be available for you to checkout the current ranking of your implementation.  
[hw2a](#)  
[hw2b](#)
6. Resources are limited, start your work ASAP. Do not leave it until the last day!