



UNIVERSITY
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High Performance Computing and Big Data

Assignment 3: MPI and OpenMP

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1 Implementation

In this section, we present the implementation details of the parallelized Game of Life simulation using MPI and OpenMP. The implementation focuses on distributing the computational workload among multiple MPI processes and leveraging OpenMP for parallelism within each process.

The chosen implementation path leverages a parallelized approach to simulate Conway's Game of Life using a combination of MPI (Message Passing Interface) and OpenMP (Open Multi-Processing) for distributed and shared-memory parallelism, respectively. The code begins by initializing MPI and determining the rank and size of each process within the MPI communicator. The board is divided horizontally into blocks, with each process responsible for a distinct segment. The parallelization is achieved by employing OpenMP directives, specifically in the computation of cell states during each iteration. Notably, the implementation demonstrates efficient communication between neighboring processes using MPI, ensuring synchronization and exchange of boundary data. Additionally, the code incorporates verification checks at specified iterations, comparing the population of a predefined pattern against expected values. The implementation not only achieves the parallelization of the Game of Life algorithm but also includes robust error handling and execution time measurements. The choice of this implementation path aligns with the goal of harnessing both MPI and OpenMP to attain a high-performance parallel simulation of the Game of Life across multiple processes and threads.

1.1 Header and Library Inclusions

```
1 #include <stdio.h>
2 #include <stdint.h>
3 #include <stdlib.h>
4 #include <mpi.h>
5 #include <omp.h>
6 #include <stdbool.h>
```

Listing 1: Header and Library Inclusions

These lines include the necessary standard C libraries and MPI (Message Passing Interface) library for parallel processing.

1.2 Constants and Definitions

```
8 // Constants defining the size of the board and maximum iterations
9 #define BOARD_SIZE 3000
10 #define MAX_ITERATIONS 5000
11
12 // Constants defining the starting positions of various patterns on the board
13 #define GROWER_START_ROW 1500
14 #define GROWER_START_COL 1500
15 #define GLIDER_START_ROW 1500
16 #define GLIDER_START_COL 1500
17 #define BEEHIVE_START_ROW 1500
18 #define BEEHIVE_START_COL 1500
19
20 // Population expectations for verification at specific iterations
21 #define GROWER_POPULATION_GEN10 49
22 #define GROWER_POPULATION_GEN100 138
23 #define GLIDER_POPULATION 5
24 #define BEEHIVE_POPULATION 6
25
```

```

26 // Debug printing controls
27 #define DEBUG_PRINT_RANK_INFO 0
28 #define DEBUG_PRINT_REGION 0
29 #define DEBUG_RUN_VERIFICATION_CHECKS 0
30 #define DEBUG_PRINT_TOTAL_POPULATION 0
31 #define DEBUG_PRINT_EXECUTION_TIME 1

```

Listing 2: Constants and Definitions

Here, we define constants for the board size, maximum iterations, starting positions of patterns, and debug controls.

1.3 Pattern Definitions

```

33 // Include patterns
34 #include "grower.h"
35 #include "glider.h"
36 #include "beehive.h"

```

Listing 3: Pattern Definitions

Imports the patterns (grower, glider, beehive) that will be placed on the board.

1.4 Utility Macros and Functions

```

38 // Macro to convert 2D indices to a 1D index for a flattened array
39 #define INDEX(row, col) ((row) * BOARD_SIZE + (col))
40
41 // Function to convert local coordinates to global coordinates
42 void local_coords_to_global(int *global_row, int *global_col, int row, int col, int
    startRow, int startCol) {
43     *global_row = row + startRow;
44     *global_col = col + startCol;
45 }
46
47 // Function to print a region of the board
48 void print_region(uint8_t *board, int startRow, int startCol, int height, int width)
    {
49     for (int i = startRow; i < startRow + height; ++i) {
50         for (int j = startCol; j < startCol + width; ++j) {
51             printf("%c", board[INDEX(i, j)] ? '#' : '^');
52         }
53         printf("\n");
54     }
55 }

```

Listing 4: Utility Macros and Functions

Defines a macro for converting 2D indices to a 1D index and functions for converting local coordinates to global coordinates and printing a region of the board.

1.5 Initialization and Population Counting

```

57 // Function to initialize the local board with a specific pattern
58 void initialize_local_board(uint8_t *board, int block_start, int block_size) {
59     // Fill the local board with the grower pattern
60     // Only the part of the pattern that is within the local board boundaries will be
        copied
61     for (int i = 0; i < block_size + 2; ++i) {

```

```

62     for (int j = 0; j < BOARD_SIZE; ++j) {
63         if (i == 0 || i == block_size + 1) {
64             // Set boundary rows to 0
65             board[INDEX(i, j)] = 0;
66             continue;
67         }
68         int row_global, col_global;
69         local_coords_to_global(&row_global, &col_global, i, j, block_start, 0);
70         if (row_global >= GROWER_START_ROW && row_global < GROWER_START_ROW +
GROWER_HEIGHT &&
71             col_global >= GROWER_START_COL && col_global < GROWER_START_COL +
GROWER_WIDTH) {
72             // Copy the grower pattern to the local board
73             board[INDEX(i, j)] = grower[row_global - GROWER_START_ROW][col_global
- GROWER_START_COL];
74         } else
75             // Set cells outside the grower pattern to 0
76             board[INDEX(i, j)] = 0;
77     }
78 }
79 }
80
81 // Function to calculate the population of the local board
82 int local_board_population(uint8_t *board, int block_size) {
83     int population = 0;
84     for (int i = 1; i <= block_size; ++i) {
85         for (int j = 0; j < BOARD_SIZE; ++j) {
86             population += board[INDEX(i, j)];
87         }
88     }
89     return population;
90 }

```

Listing 5: Initialization and Population Counting

Functions for initializing the local board with the grower pattern and counting the population of the local board.

1.6 Game of Life Rules

```

92 // Function to apply the Game of Life rules to a cell
93 uint8_t apply_rules(int current_state, int neighbors) {
94     if (current_state == 1) {
95         // Cell is alive
96         if (neighbors < 2 || neighbors > 3) {
97             // Rule 1 and 3: Cell dies
98             return 0;
99         } else {
100             // Rule 2: Cell survives
101             return 1;
102         }
103     } else {
104         // Cell is dead
105         if (neighbors == 3) {
106             // Rule 4: Cell becomes alive
107             return 1;
108         } else {
109             // Cell remains dead
110             return 0;
111         }
112     }
113 }

```

```

112     }
113 }

```

Listing 6: Game of Life Rules

Defines the rules for the Game of Life, determining whether a cell survives, dies, or becomes alive (as described here).

1.7 Game of Life Iterations

```

115 // Function to run one iteration of the Game of Life for the local region of the
    board
116 void run_game_of_life(uint8_t *current, uint8_t *next, int block_size) {
117 #pragma omp parallel for collapse(2)
118     for (int i = 1; i <= block_size; ++i) {
119         for (int j = 0; j < BOARD_SIZE; ++j) {
120             // Count neighbors for each cell
121             int neighbors = 0;
122             for (int ni = -1; ni <= 1; ++ni) {
123                 for (int nj = -1; nj <= 1; ++nj) {
124                     if (ni == 0 && nj == 0) continue;
125
126                     int ni_ = i + ni;
127
128                     // Check if the neighbor is within the local board boundaries
129                     int nj_ = j + nj;
130
131                     // Check if the neighbor is within the board boundaries
132                     if (nj_ >= 0 && nj_ < BOARD_SIZE) {
133                         neighbors += current[INDEX(ni_, nj_)];
134                     }
135                 }
136             }
137
138             // Apply Game of Life rules
139             next[INDEX(i, j)] = apply_rules(current[INDEX(i, j)], neighbors);
140         }
141     }
142 }

```

Listing 7: Game of Life Iterations

Includes the parallelized code for running one iteration of the Game of Life for the local region of the board using OpenMP.

1.8 Global Population Calculation

```

144 // Function to calculate the population of the entire board across all processes
145 int total_board_population(uint8_t *local_board, int block_size) {
146     int local_population = local_board_population(local_board, block_size);
147
148     // Use MPI_Allreduce to perform a reduction operation across all processes
149     int total_population;
150     if (MPI_Allreduce(&local_population, &total_population, 1, MPI_INT, MPI_SUM,
        MPI_COMM_WORLD) != MPI_SUCCESS) {
151         fprintf(stderr, "Error in MPI_Allreduce operation.\n");
152         exit(EXIT_FAILURE);
153     }
154 }

```

```

155     return total_population;
156 }

```

Listing 8: Global Population Calculation

Calculates the population of the entire board across all processes using MPI.Allreduce.

1.9 Verification Checks

```

158 // Function to perform verification checks at specific iterations
159 void run_verification(uint8_t *local_board, int iter, int block_size) {
160     // Check total population for specific iterations
161     if (iter == 10) {
162         int total_population = total_board_population(local_board, block_size);
163         printf("Generation 10: Grower pattern population = %d\n", total_population);
164         if (total_population != GROWER_POPULATION_GEN10) {
165             printf("ERROR: Incorrect population for generation 10\n");
166             exit(1);
167         }
168     }
169
170     if (iter == 100) {
171         int total_population = total_board_population(local_board, block_size);
172         printf("Generation 100: Grower pattern population = %d\n", total_population);
173         if (total_population != GROWER_POPULATION_GEN100) {
174             printf("ERROR: Incorrect population for generation 100\n");
175             exit(1);
176         }
177     }
178 }

```

Listing 9: Verification Checks

Includes checks for total population at specific iterations and terminates with an error if the population is incorrect.

1.10 Main Function and MPI Initialization

```

180 int main(int argc, char *argv[]) {
181     int rank, size;
182
183     // Start up MPI
184     if (MPI_Init(&argc, &argv) != MPI_SUCCESS) {
185         fprintf(stderr, "Error initializing MPI.\n");
186         exit(EXIT_FAILURE);
187     }
188     if (MPI_Comm_rank(MPI_COMM_WORLD, &rank) != MPI_SUCCESS) {
189         fprintf(stderr, "Error in MPI_Comm_rank.\n");
190         exit(EXIT_FAILURE);
191     }
192     if (MPI_Comm_size(MPI_COMM_WORLD, &size) != MPI_SUCCESS) {
193         fprintf(stderr, "Error in MPI_Comm_size.\n");
194         exit(EXIT_FAILURE);
195     }
196
197     const bool am_master = 0 == rank;
198
199     // Divide the board into blocks for parallel processing (horizontal segments)
200     int block_size = BOARD_SIZE / size;
201     int block_start = rank * block_size;

```

```

202     int block_end = block_start + block_size;
203     if (DEBUG_PRINT_RANK_INFO) {
204         // Print the block start and end indices for each process
205         printf("Rank %d: Block start = %d, Block end = %d\n", rank, block_start,
block_end);
206     }
207
208     // Allocate memory for the local and next generation boards
209     uint8_t *local_board = (uint8_t *) malloc(BOARD_SIZE * (block_size + 2) * sizeof(
uint8_t));
210     uint8_t *next_gen_board = (uint8_t *) malloc(BOARD_SIZE * (block_size + 2) *
sizeof(uint8_t));
211
212     if (local_board == NULL || next_gen_board == NULL) {
213         fprintf(stderr, "Error allocating memory.\n");
214         exit(EXIT_FAILURE);
215     }
216
217     // Initialize the local board with the grower pattern
218     initialize_local_board(local_board, block_start, block_size);
219
220     // Record the start time for measuring execution time
221     double start_time = MPI_Wtime();
222
223     for (int iter = 0; iter < MAX_ITERATIONS; ++iter) {
224         if (DEBUG_PRINT_RANK_INFO) {
225             // Print the population of the local board for each iteration
226             printf("Rank %d: Iteration %d, Population = %d\n", rank, iter,
local_board_population(local_board, block_size));
227         }
228
229         if (DEBUG_PRINT_REGION) {
230             print_region(local_board, GROWER_START_ROW, GROWER_START_COL,
GROWER_HEIGHT, GROWER_WIDTH);
231         }
232
233         if (DEBUG_RUN_VERIFICATION_CHECKS) {
234             // Verification checks for specific iterations
235             run_verification(local_board, iter, block_size);
236         }
237
238         if (DEBUG_PRINT_TOTAL_POPULATION && am_master) {
239             // Calculate and print the total population of the entire board
240             int total_population = total_board_population(local_board, block_size);
241             printf("Total population after iteration %d: %d\n", iter,
total_population);
242         }
243
244         // Communication between neighboring processes using MPI
245         // Identify left and right neighbors, set MPI_PROC_NULL if at the boundary
246         int left_neighbour = (rank == 0) ? MPI_PROC_NULL : (rank - 1);
247         int right_neighbour = (rank == size - 1) ? MPI_PROC_NULL : (rank + 1);
248
249         // Define MPI request objects for non-blocking communication
250         MPI_Request left_send_request, right_send_request;
251         MPI_Request left_recv_request, right_recv_request;
252
253         // Initiate non-blocking send operations to left and right neighbors
254         if (block_start > 0) {
255             // Communication with the left neighbor

```

```

257         if (MPI_Isend(&local_board[INDEX(1, 0)], BOARD_SIZE, MPI_UINT8_T,
258 left_neighbour, 0, MPI_COMM_WORLD,
259 &left_send_request) != MPI_SUCCESS) {
260             fprintf(stderr, "Error in MPI_Isend to left neighbor.\n");
261             exit(EXIT_FAILURE);
262         }
263         if (MPI_Irecv(&local_board[INDEX(0, 0)], BOARD_SIZE, MPI_UINT8_T,
264 left_neighbour, 0, MPI_COMM_WORLD,
265 &left_recv_request) != MPI_SUCCESS) {
266             fprintf(stderr, "Error in MPI_Irecv from left neighbor.\n");
267             exit(EXIT_FAILURE);
268         }
269     }
270     if (block_end < BOARD_SIZE) {
271         // Communication with the right neighbor
272         if (MPI_Isend(&local_board[INDEX(block_size, 0)], BOARD_SIZE, MPI_UINT8_T,
273 right_neighbour, 0,
274 MPI_COMM_WORLD,
275 &right_send_request) != MPI_SUCCESS) {
276             fprintf(stderr, "Error in MPI_Isend to right neighbor.\n");
277             exit(EXIT_FAILURE);
278         }
279         if (MPI_Irecv(&local_board[INDEX(block_size + 1, 0)], BOARD_SIZE,
280 MPI_UINT8_T, right_neighbour, 0,
281 MPI_COMM_WORLD, &right_recv_request) != MPI_SUCCESS) {
282             fprintf(stderr, "Error in MPI_Irecv from right neighbor.\n");
283             exit(EXIT_FAILURE);
284         }
285     }
286     // Wait for completion of all non-blocking communication operations
287     if (block_start > 0) {
288         if (MPI_Wait(&left_send_request, MPI_STATUS_IGNORE) != MPI_SUCCESS) {
289             fprintf(stderr, "Error in MPI_Wait for left_send_request.\n");
290             exit(EXIT_FAILURE);
291         }
292         if (MPI_Wait(&left_recv_request, MPI_STATUS_IGNORE) != MPI_SUCCESS) {
293             fprintf(stderr, "Error in MPI_Wait for left_recv_request.\n");
294             exit(EXIT_FAILURE);
295         }
296     }
297     if (block_end < BOARD_SIZE) {
298         if (MPI_Wait(&right_send_request, MPI_STATUS_IGNORE) != MPI_SUCCESS) {
299             fprintf(stderr, "Error in MPI_Wait for right_send_request.\n");
300             exit(EXIT_FAILURE);
301         }
302         if (MPI_Wait(&right_recv_request, MPI_STATUS_IGNORE) != MPI_SUCCESS) {
303             fprintf(stderr, "Error in MPI_Wait for right_recv_request.\n");
304             exit(EXIT_FAILURE);
305         }
306     }
307     // Run one iteration of the Game of Life for the local region
308     run_game_of_life(local_board, next_gen_board, block_size);
309     // Swap pointers to update the local board for the next iteration
310     uint8_t *temp = local_board;
311     local_board = next_gen_board;
312     next_gen_board = temp;

```



```

313 }
314
315 // Record the end time for measuring execution time
316 double end_time = MPI_Wtime();
317
318 // Print total execution time
319 if (DEBUG_PRINT_EXECUTION_TIME && am_master) {
320     printf("Total execution time: %f seconds\n", end_time - start_time);
321 }
322
323 // Print the final time : the time taken by the slowest process to complete the
324 // execution
325 double max_time;
326 if (MPI_Reduce(&end_time, &max_time, 1, MPI_DOUBLE, MPI_MAX, 0, MPI_COMM_WORLD)
327     != MPI_SUCCESS) {
328     fprintf(stderr, "Error in MPI_Reduce operation.\n");
329     exit(EXIT_FAILURE);
330 }
331 printf("Max execution time: %f seconds\n", max_time - start_time);
332
333 // Free allocated memory
334 free(local_board);
335 free(next_gen_board);
336
337 // Finalize MPI
338 if (MPI_Finalize() != MPI_SUCCESS) {
339     fprintf(stderr, "Error finalizing MPI.\n");
340     exit(EXIT_FAILURE);
341 }
342
343 return 0;
344 }

```

Listing 10: Main Function and MPI Initialization

The main function initializes MPI, divides the board into blocks for parallel processing, allocates memory, runs iterations, performs MPI communication, and finalizes MPI.

2 Data distribution and communication method

In the provided code, the data distribution strategy involves dividing the Game of Life board into horizontal segments, creating a strip-like decomposition. Each MPI process is assigned a specific segment of the board, responsible for computing the Game of Life rules within that local region. The primary communication occurs between neighboring processes to exchange boundary information necessary for the computation of the next generation. For each process, the left and right neighbors are identified, and non-blocking MPI send and receive operations are employed to facilitate data exchange.

Specifically, communication involves sending and receiving entire rows of cells between neighboring processes. The left neighbor sends its rightmost row to the current process, and the right neighbor sends its leftmost row. This horizontal exchange of boundary data ensures that each process has the required information to apply the Game of Life rules accurately within its local segment. The `MPI_Wait` function is utilized to synchronize these non-blocking communication operations, ensuring proper coordination and data consistency throughout the parallel simulation. This communication strategy effectively balances computation and communication, contributing to the scalability of the simulation across multiple MPI processes.

3 Speedup

Table 1 summarizes the execution times of the parallel Game of Life implementation across various process configurations that were run on the Snellius cluster, using one node. Each row corresponds to a specific total number of processes/threads (specifically the product of the two), and the columns represent different configurations within that total. The "Max Execution Time" column indicates the highest execution time observed for a given configuration. The table provides insights into the scalability of the parallel implementation, demonstrating improved performance as the number of processes increases.

The speedup (S) is calculated using the formula:

$$S = \frac{T_{\text{serial}}}{T_{\text{parallel}}}$$

where T_{serial} is the execution time in a serial (non-parallel) setting, and T_{parallel} is the (maximum) execution time in a parallel setting.

Total Processes*Threads	#Processes	#Threads per process	Execution Time (s)	Max Exec Time (s)	Speedup
1	1	1	206.133195	206.133195	-
2	1 2	2 1	103.484263 103.491485	103.491485	1.99
4	1 2 4	4 2 1	51.930277 51.929517 51.907608	51.930277	3.97
8	1 2 4 8	8 4 2 1	26.050067 26.005198 26.036027 25.957004	26.050067	7.91
16	1 2 4 8 16	16 8 4 2 1	13.020182 13.044554 13.068875 13.057330 13.000273	13.020182	15.83
32	1 2 4 8 16 32	32 16 8 4 2 1	6.519567 6.532024 6.513430 6.515856 6.492571 6.438125	6.519567	31.62
64	1 2 4 8 16 32 64	64 32 16 8 4 2 1	3.341772 3.307247 3.267373 3.318634 3.294378 3.262157 3.162100	3.341772	61.68
128	1 2 4 8 16 32 64 128	128 64 32 16 8 4 2 1	9.926397 2.182159 6.728790 7.027649 7.674845 2.285173 1.958015 7.117786	9.926397	20.77

Table 1: Benchmark Results for Parallel Game of Life

The speedup analysis is visualized in Figure 1, where the speedup (last column of Table 1) is plotted against the total number of processes/threads (first column of Table 1). The rounded speedup values are annotated on the data points for clarity.

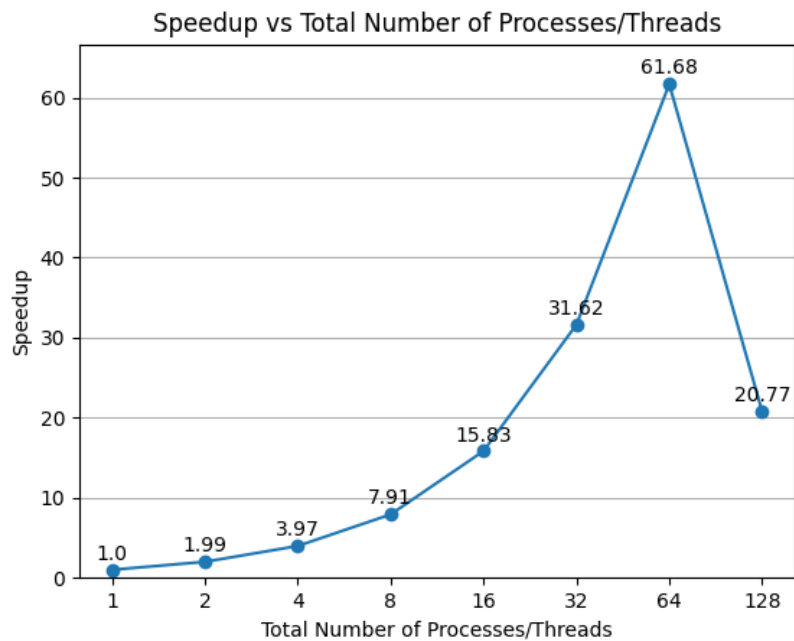


Figure 1: Speedup vs Total Number of Processes/Threads

4 Population Growth

In the context of the provided Game of Life simulation, it is noteworthy that after 5000 generations, the final population is at 3647 living cells.

The growth chart (Figure 2), visually encapsulates this evolution, showcasing the population fluctuations until reaching the state of 3647 cells after the specified number of iterations.

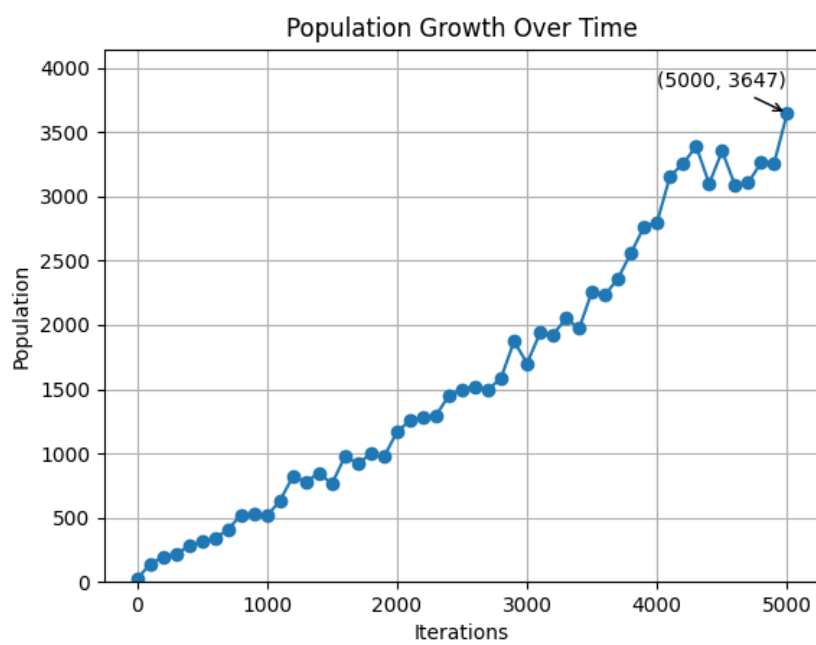


Figure 2: Population Growth Over 5000 Generations