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Course: Parallel and Distributed Computing

Assignment: 2

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Date: 7 May 2025

Task 1:

Problem Statement

Write an MPI program that assigns different roles to each process based on its rank:

- Process 0: Master (coordinator) - reads an array of 16 integers and distributes segments to all processes.
- All Other Processes: Workers - receive their portion, compute the square of each value, and send results back.

1. Implement this using MPI_Send and MPI_Recv. 2. Master process should collect results and display the final array. 3. Add support for arbitrary number of processes ≤ 16 .

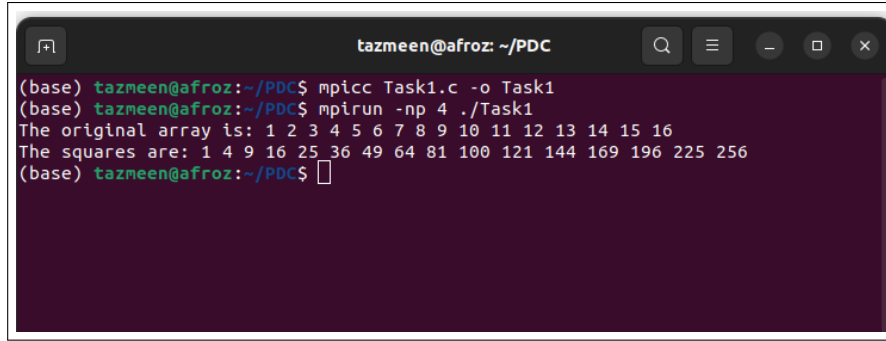
Implementation

```
1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <mpi.h>
4
5 int main(int argc , char **argv){
6     //rank - process id
7     //process_count - number of processes
8     //MPI_Init - initializes the MPI environment
9     //MPI_Comm_rank - gets the rank of the process
10    //MPI_Comm_size - gets the number of processes
11    //MPI_COMM_WORLD - communicator that includes all processes
12    int rank, process_count;
13    MPI_Init(&argc, &argv);
14    MPI_Comm_rank(MPI_COMM_WORLD, &rank);
15    MPI_Comm_size(MPI_COMM_WORLD, &process_count);
16
17    int array[16];
18    // Calculate the number of elements each worker process will handle
19    //equally distribute the elements among the worker processes and if
20    //there are remaining elements, distribute them one by one to the first
21    //few processes
22    int elements_per_process = 16 / (process_count - 1);
23    int remaining_elements = 16 % (process_count - 1);
24
25    if(rank == 0){
26        for(int i = 0; i < 16; i++){
27            array[i] = i + 1;
28        }
29
30        printf("The original array is: ");
31        for(int i = 0; i < 16; i++){
32            printf("%d ", array[i]);
33        }
34        printf("\n");
35        // Distribute the array to all worker processes
36        int start_index = 0;
37        for(int i = 1; i < process_count; i++){
```

```

38         int count = elements_per_process;
39         if(i <= remaining_elements) {
40             count += 1; // Add 1 if there are remaining elements
41             because one process will have one more element
42             MPI_Send(&array[start_index], count, MPI_INT, i, 0,
MPI_COMM_WORLD);
43             start_index += count;
44         }
45
46         // Collect results from all worker processes
47         start_index = 0;
48         for(int i = 1; i < process_count; i++){
49             int count = elements_per_process;
50             if(i <= remaining_elements) {
51                 count += 1; // Add 1 if there are remaining elements
52             }
53             MPI_Recv(&array[start_index], count, MPI_INT, i, 1,
MPI_COMM_WORLD, MPI_STATUS_IGNORE);
54             start_index += count;
55         }
56         // Print the results
57         printf("The squares are: ");
58         for(int i = 0; i < 16; i++){
59             printf("%d ", array[i]);
60         }
61         printf("\n");
62     } else {
63         // Worker processes receive their portion of the array
64         int count = elements_per_process;
65         if(rank <= remaining_elements) {
66             count += 1;
67         }
68         int sub_array[count];
69         MPI_Recv(sub_array, count, MPI_INT, 0, 0, MPI_COMM_WORLD,
MPI_STATUS_IGNORE);
70
71         // Compute the square of each value
72         for(int i = 0; i < count; i++){
73             sub_array[i] = sub_array[i] * sub_array[i];
74         }
75
76         // Send the results back to the root process
77         MPI_Send(sub_array, count, MPI_INT, 0, 1, MPI_COMM_WORLD);
78     }
79
80     MPI_Finalize();
81     return 0;
82 }

```

A terminal window with a dark background and light-colored text. The window title is 'tazmeen@afroz: ~/PDC'. The prompt is '(base)'. The user has entered 'mpicc Task1.c -o Task1'. The prompt is '(base)'. The user has entered 'mpirun -np 4 ./Task1'. The output is 'The original array is: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16' followed by 'The squares are: 1 4 9 16 25 36 49 64 81 100 121 144 169 196 225 256'. The prompt is '(base)'. The user has entered a space character.

```
(base) tazmeen@afroz:~/PDC$ mpicc Task1.c -o Task1
(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task1
The original array is: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
The squares are: 1 4 9 16 25 36 49 64 81 100 121 144 169 196 225 256
(base) tazmeen@afroz:~/PDC$ 
```

Figure 1: Output of Task 1 implementation

Questions

a. How is workload distribution affected by the number of processes?

The workload is evenly distributed among worker processes, with extra elements assigned to the first few processes if the array size is not evenly divisible. As the number of processes increases, each worker receives fewer elements to process, potentially improving performance until communication overhead begins to dominate.

b. Can this design scale for larger arrays? Why or why not?

The design can handle larger arrays but may face communication bottlenecks due to the root process. The current design uses a single root process to coordinate all communication. This limits scalability because the root process cannot distribute or collect data in parallel, becoming a bottleneck as the array size or number of processes increases.

Task 2: Safe Non-Blocking Communication

Problem Statement

Modify Task 1 to use non-blocking versions: `MPI_Isend`, `MPI_Irecv`, and `MPI_Waitall`.

1. Create an array `requests[]` to manage multiple asynchronous communications.
2. Ensure correct synchronization using `MPI_Waitall`.

Implementation

```
1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <mpi.h>
4
5 int main(int argc , char **argv){
6     int rank, process_count;
7     MPI_Init(&argc, &argv);
8     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
9     MPI_Comm_size(MPI_COMM_WORLD, &process_count);
10
11     int array[16];
12     int elements_per_process = 16 / (process_count - 1);
13     int remaining_elements = 16 % (process_count - 1);
14
15     if(rank == 0){
16         for(int i = 0; i < 16; i++){
17             array[i] = i + 1;
18         }
19
20         printf("The original array is: ");
21         for(int i = 0; i < 16; i++){
22             printf("%d ", array[i]);
23         }
24         printf("\n");
25
26         // Arrays to manage asynchronous communication
27         MPI_Request send_requests[process_count - 1];
28         MPI_Request recv_requests[process_count - 1];
29
30         // Distribute the array to all worker processes
31         int start_index = 0;
32         for(int i = 1; i < process_count; i++){
33             int count = elements_per_process;
34             if(i <= remaining_elements) {
35                 count += 1;
36             }
37             MPI_Isend(&array[start_index], count, MPI_INT, i, 0,
MPI_COMM_WORLD, &send_requests[i - 1]);
38             start_index += count;
39         }
40
41         // Collect results from all worker processes
```

```

42     start_index = 0;
43     for(int i = 1; i < process_count; i++){
44         int count = elements_per_process;
45         if(i <= remaining_elements) {
46             count += 1;
47         }
48         MPI_Irecv(&array[start_index], count, MPI_INT, i, 1,
MPI_COMM_WORLD, &recv_requests[i - 1]);
49         start_index += count;
50     }
51
52     // Wait for all sends and receives to complete
53     MPI_Waitall(process_count - 1, send_requests, MPI_STATUSES_IGNORE)
;
54     MPI_Waitall(process_count - 1, recv_requests, MPI_STATUSES_IGNORE)
;
55
56     // Print the results
57     printf("The squares are: ");
58     for(int i = 0; i < 16; i++){
59         printf("%d ", array[i]);
60     }
61     printf("\n");
62 } else {
63     // Worker processes receive their portion of the array
64     int count = elements_per_process;
65     if(rank <= remaining_elements) {
66         count += 1;
67     }
68     int sub_array[count];
69     MPI_Request recv_request, send_request;
70
71     MPI_Irecv(sub_array, count, MPI_INT, 0, 0, MPI_COMM_WORLD, &
recv_request);
72     MPI_Wait(&recv_request, MPI_STATUS_IGNORE);
73
74     // Compute the square of each value
75     for(int i = 0; i < count; i++){
76         sub_array[i] = sub_array[i] * sub_array[i];
77     }
78
79     // Send the results back to the root process
80     MPI_Isend(sub_array, count, MPI_INT, 0, 1, MPI_COMM_WORLD, &
send_request);
81     MPI_Wait(&send_request, MPI_STATUS_IGNORE);
82 }
83
84 MPI_Finalize();
85 return 0;
86 }

```

```
(base) tazmeen@afroz:~/PDC$ mpicc Task2.c -o Task2
(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task2
The original array is: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
The squares are: 1 2 3 4 25 36 49 64 81 100 121 144 169 196 225 256
(base) tazmeen@afroz:~/PDC$
```

Figure 2: Output of Task 2 implementation

Questions

a. Explain why MPI_Waitall is needed.

Non-blocking operations like MPI_Isend and MPI_Irecv initiate communication but do not wait for it to complete. This allows the program to continue executing other tasks while the communication happens in the background. MPI_Waitall ensures that all initiated non-blocking operations in the MPI_Request array are completed before moving forward. Without it, the program might proceed prematurely, leading to undefined behavior or incomplete communication.

b. What happens if you omit waiting for non-blocking messages? Simulate it and report.

Omitting the wait for non-blocking messages can lead to accessing incomplete data, modifying send buffers too early, and memory corruption from premature buffer reuse. It may also cause the program to finish before communication completes, resulting in data loss. In simulation, skipping MPI_Waitall led to inconsistent outputs, incorrect values, and occasional crashes across multiple runs.

Task 3: Custom Communication Protocol

Problem Statement

Write an MPI program with at least 4 processes, using the following logic:

- Process 0 sends two arrays to Process 1 and 2.
- Process 1 and 2 process the arrays and send results to Process 3.
- Process 3 performs final aggregation and displays the result.

1. Use different tags for each message. 2. Use MPI_Status in receiving functions to determine source and tag dynamically.

Implementation

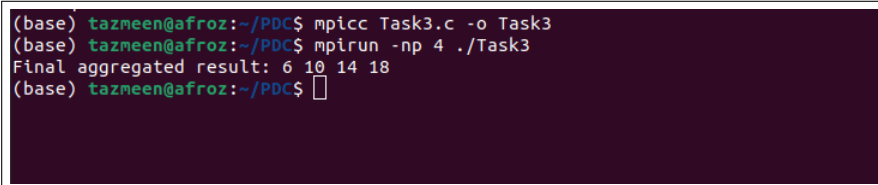
```
1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <mpi.h>
4
5 int main(int argc , char **argv){
6     int rank, process_count;
7     MPI_Init(&argc, &argv);
8     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
9     MPI_Comm_size(MPI_COMM_WORLD, &process_count);
10
11     // Write an MPI program with at least 4 processes, using the following
12     // logic: - Process 0 sends two arrays to Process 1 and 2.
13     // - Process 1 and 2 process the arrays and send results to Process 3.
14     // - Process 3 performs final aggregation and displays the result.
15     // 1. Use different tags for each message.
16     // 2. Use MPI_Status in receiving functions to determine source and
17     // tag dynamically.
18
19     int array1[4], array2[4];
20     int result1[4], result2[4];
21     int final_result[4];
22     MPI_Status status;
23     if(rank == 0){
24         // Initialize the arrays
25         for(int i = 0; i < 4; i++){
26             array1[i] = i + 1;
27             array2[i] = i + 2;
28         }
29         // Send the arrays to Process 1 and Process 2
30         MPI_Send(array1, 4, MPI_INT, 1, 0, MPI_COMM_WORLD);
31         MPI_Send(array2, 4, MPI_INT, 2, 1, MPI_COMM_WORLD);
32     } else if(rank == 1){
33         // Receive the first array from Process 0
34         MPI_Recv(array1, 4, MPI_INT, 0, 0, MPI_COMM_WORLD, &status);
35         // Process the array (summing each element)
36         for(int i = 0; i < 4; i++){
37             result1[i] = array1[i] + array1[i];
38         }
39     }
```



```

37     // Send the result to Process 3
38     MPI_Send(result1, 4, MPI_INT, 3, 2, MPI_COMM_WORLD);
39 } else if(rank == 2){
40     // Receive the second array from Process 0
41     MPI_Recv(array2, 4, MPI_INT, 0, 1, MPI_COMM_WORLD, &status);
42     // Process the array (summing each element)
43     for(int i = 0; i < 4; i++){
44         result2[i] = array2[i] + array2[i];
45     }
46     // Send the result to Process 3
47     MPI_Send(result2, 4, MPI_INT, 3, 3, MPI_COMM_WORLD);
48 } else if(rank == 3){
49     // Receive results from Process 1 and Process 2
50     MPI_Recv(result1, 4, MPI_INT, 1, 2, MPI_COMM_WORLD, &status);
51     MPI_Recv(result2, 4, MPI_INT, 2, 3, MPI_COMM_WORLD, &status);
52
53     // Aggregate results
54     for(int i = 0; i < 4; i++){
55         final_result[i] = result1[i] + result2[i];
56     }
57
58     // Display the final result
59     printf("Final aggregated result: ");
60     for(int i = 0; i < 4; i++){
61         printf("%d ", final_result[i]);
62     }
63
64     printf("\n");
65
66 }
67 MPI_Finalize();
68 return 0;
69 }

```



```

(base) tazmeen@afroz:~/PDC$ mpicc Task3.c -o Task3
(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task3
Final aggregated result: 6 10 14 18
(base) tazmeen@afroz:~/PDC$

```

Figure 3: Output of Task 3 implementation

Questions

a. How do message tags help in handling multiple simultaneous messages?

When multiple messages are sent to the same process, tags ensure that the receiving process can handle each message appropriately. For example, in my code:

- Process 3 uses tags 2 and 3 to distinguish between results from Process 1 and Process 2

- Without tags, Process 3 would not know which incoming message corresponds to which computation
- Tags allow the receiver to selectively receive messages in a specific order, regardless of when they arrive
- This enables more complex communication patterns and workflows

b. What can go wrong if two messages arrive with the same tag from different sources?

If two messages with the same tag arrive from different sources, the receiving process cannot distinguish between them based on the tag alone. This may lead to processing the wrong message or overwriting data. If the process doesn't check the source using `MPI_SOURCE` in the `MPI_Status`, it risks handling a message from an unintended source

For example: If Process 3 in my code receives two messages with tag 2 (one from Process 1 and one from Process 2), it cannot determine which message corresponds to which source without checking `MPI_SOURCE` in the status object.

Task 4: Implement Circular Ping-Pong

Problem Statement

Create a ring of N processes ($N \geq 4$), where each process passes a counter to the next process in the ring. The counter starts at 0 and is incremented on each pass.

1. Process 0 starts the counter.
2. After M complete cycles, the process 0 terminates the loop and ends execution on all processes.

Requirements:

- Implement safe termination using message flags.
- Avoid deadlocks.

Implementation

```
1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <mpi.h>
4
5
6
7 int main(int argc, char **argv) {
8     int world_rank, world_size;
9
10
11     MPI_Init(&argc, &argv);
12     MPI_Comm_rank(MPI_COMM_WORLD, &world_rank);
13     MPI_Comm_size(MPI_COMM_WORLD, &world_size);
14
15     // Check if we have enough processes
16     if (world_size < 4) {
17         if (world_rank == 0) {
18             printf("Error: This program requires at least 4 processes.\n");
19         }
20         MPI_Finalize();
21         return 1;
22     }
23
24
25     int counter = 0;
26     int M = 2; // Number of complete cycles
27     int cycles_completed = 0;
28     MPI_Status status;
29
30     // Define next and previous ranks
31     // rank 1 then next rank = (0 + 1) % 4 = 1
32     // rank 1 then prev rank = (0 + 4 - 1) % 4 = 3
33     int next_rank = (world_rank + 1) % world_size;
34     int prev_rank = (world_rank + world_size - 1) % world_size;
```

```

35
36
37     if (world_rank == 0) {
38         printf("Process %d: Starting counter with value %d\n", world_rank,
39             counter);
40
41         // Send initial counter
42         counter++; // Increment
43         printf("Process %d: Sending counter with value %d to process %d\n",
44             world_rank, counter, next_rank);
45         MPI_Send(&counter, 1, MPI_INT, next_rank, 0, MPI_COMM_WORLD);
46
47         // Main loop for process 0
48         while (cycles_completed < M) {
49             // Receive the counter after a complete cycle
50             MPI_Recv(&counter, 1, MPI_INT, prev_rank, 0, MPI_COMM_WORLD, &
51                 status);
52             printf("Process %d: Received counter with value %d from
53                 process %d\n",
54                 world_rank, counter, prev_rank);
55
56             // Increment cycles counter
57             cycles_completed++;
58             printf("Process %d: Completed cycle %d of %d\n", world_rank,
59                 cycles_completed, M);
60
61             if (cycles_completed < M) {
62                 // Continue with another cycle
63                 counter++; // Increment counter
64                 printf("Process %d: Sending counter with value %d to
65                     process %d\n",
66                     world_rank, counter, next_rank);
67                 MPI_Send(&counter, 1, MPI_INT, next_rank, 0,
68                     MPI_COMM_WORLD);
69             }
70         }
71
72         // Send termination message to next process after all cycles are
73         complete
74         printf("Process %d: All %d cycles completed, initiating
75             termination\n", world_rank, M);
76         MPI_Send(&counter, 1, MPI_INT, next_rank, 1, MPI_COMM_WORLD);
77
78     } else {
79         // Other processes just pass along the counter until terminated
80         while (1) {
81             // Receive message from previous process
82             MPI_Recv(&counter, 1, MPI_INT, prev_rank, MPI_ANY_TAG,
83                 MPI_COMM_WORLD, &status);
84
85             // Check the tag to see if it's a termination message
86             if (status.MPI_TAG == 1) {
87                 printf("Process %d: Received termination signal,

```

```

79     forwarding to process %d\n",
80         world_rank, next_rank);
81
82     // Forward the termination message and exit the loop
83     MPI_Send(&counter, 1, MPI_INT, next_rank, 1,
84             MPI_COMM_WORLD);
85     break;
86 }
87
88 // Regular counter message - process and forward
89 printf("Process %d: Received counter with value %d from
90 process %d\n",
91         world_rank, counter, prev_rank);
92
93 counter++; // Increment counter
94 printf("Process %d: Sending counter with value %d to process %
95 d\n",
96         world_rank, counter, next_rank);
97 MPI_Send(&counter, 1, MPI_INT, next_rank, 0, MPI_COMM_WORLD);
98 }
99 }
100
101 printf("Process %d: Terminating\n", world_rank);
102 MPI_Finalize();
103 return 0;
104 }

```

Questions

a. What are common pitfalls in ring-based communication?

The most common issues in ring-based communication are:

- Deadlocks: When all processes are waiting to receive before sending, creating a circular dependency
- Message routing errors: When processes send in one direction but receive from another, causing messages to never arrive
- Termination detection: Difficulty in determining when to stop the ring communication
- Error propagation: Errors in one process can cascade through the entire ring

b. What would be different if communication was bi-directional? Implement and test.

The differences between unidirectional and bi-directional ring communication include:

Message Flow

- Unidirectional: Message passes in one direction only
- Bi-directional: Messages flow in both directions (clockwise and counterclockwise)

Counters

- Unidirectional: One counter circulates the ring

```

(base) tazmeen@afroz:~/PDC$ mpicc Task4.c -o Task4
(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task4
Process 0: Starting counter with value 0
Process 0: Sending counter with value 1 to process 1
Process 1: Received counter with value 1 from process 0
Process 1: Sending counter with value 2 to process 2
Process 2: Received counter with value 2 from process 1
Process 2: Sending counter with value 3 to process 3
Process 3: Received counter with value 3 from process 2
Process 3: Sending counter with value 4 to process 0
Process 0: Received counter with value 4 from process 3
Process 0: Completed cycle 1 of 2
Process 0: Sending counter with value 5 to process 1
Process 1: Received counter with value 5 from process 0
Process 1: Sending counter with value 6 to process 2
Process 3: Received counter with value 7 from process 2
Process 3: Sending counter with value 8 to process 0
Process 0: Received counter with value 8 from process 3
Process 0: Completed cycle 2 of 2
Process 0: All 2 cycles completed, initiating termination
Process 0: Terminating
Process 2: Received counter with value 6 from process 1
Process 2: Sending counter with value 7 to process 3
Process 2: Received termination signal, forwarding to process 3
Process 2: Terminating
Process 1: Received termination signal, forwarding to process 2
Process 1: Terminating
Process 3: Received termination signal, forwarding to process 0
Process 3: Terminating
(base) tazmeen@afroz:~/PDC$ 

```

Figure 4: Output of Task 4 implementation

- Bi-directional: Two counters move in opposite directions

Termination Logic

- Unidirectional: Process 0 stops after one counter completes M cycles
- Bi-directional: Process 0 tracks both counters; terminates after both complete M cycles

Performance

- Unidirectional: Slower due to single path usage
- Bi-directional: Faster with parallel message flow, but higher overhead

```

1 // #include <stdio.h>
2 #include <stdlib.h>
3 #include <mpi.h>
4
5 int main(int argc, char **argv) {
6     int world_rank, world_size;
7
8     MPI_Init(&argc, &argv);
9     MPI_Comm_rank(MPI_COMM_WORLD, &world_rank);
10    MPI_Comm_size(MPI_COMM_WORLD, &world_size);
11
12    if (world_size < 4) {
13        if (world_rank == 0) {
14            printf("Error: This program requires at least 4 processes.\n");
15        }
16    }
17 }

```

```

16     MPI_Finalize();
17     return 1;
18 }
19
20 int counter_forward = 0;
21 int counter_backward = 0;
22 int M = 2;
23 int cycles_completed = 0;
24 MPI_Status status;
25
26 int next_rank = (world_rank + 1) % world_size;
27 int prev_rank = (world_rank + world_size - 1) % world_size;
28
29 if (world_rank == 0) {
30     printf("Process %d: Starting bidirectional communication\n",
world_rank);
31
32     // Start both directions
33     counter_forward++;
34     counter_backward++;
35     MPI_Send(&counter_forward, 1, MPI_INT, next_rank, 0,
MPI_COMM_WORLD);
36     MPI_Send(&counter_backward, 1, MPI_INT, prev_rank, 0,
MPI_COMM_WORLD);
37
38     while (cycles_completed < M) {
39         // Receive from both sides
40         MPI_Recv(&counter_backward, 1, MPI_INT, next_rank, MPI_ANY_TAG
, MPI_COMM_WORLD, &status);
41         printf("Process %d: Received BACKWARD counter = %d from %d\n",
world_rank, counter_backward, next_rank);
42
43         MPI_Recv(&counter_forward, 1, MPI_INT, prev_rank, MPI_ANY_TAG,
MPI_COMM_WORLD, &status);
44         printf("Process %d: Received FORWARD counter = %d from %d\n",
world_rank, counter_forward, prev_rank);
45
46         cycles_completed++;
47         printf("Process %d: Completed cycle %d of %d\n", world_rank,
cycles_completed, M);
48
49         if (cycles_completed < M) {
50             counter_forward++;
51             counter_backward++;
52             MPI_Send(&counter_forward, 1, MPI_INT, next_rank, 0,
MPI_COMM_WORLD);
53             MPI_Send(&counter_backward, 1, MPI_INT, prev_rank, 0,
MPI_COMM_WORLD);
54         }
55     }
56
57     // Termination signal in both directions
58     MPI_Send(&counter_forward, 1, MPI_INT, next_rank, 1,
MPI_COMM_WORLD);

```

```

59     MPI_Send(&counter_backward, 1, MPI_INT, prev_rank, 1,
MPI_COMM_WORLD);
60
61     } else {
62         while (1) {
63             // BACKWARD direction
64             MPI_Recv(&counter_backward, 1, MPI_INT, next_rank, MPI_ANY_TAG
, MPI_COMM_WORLD, &status);
65             if (status.MPI_TAG == 1) {
66                 MPI_Send(&counter_backward, 1, MPI_INT, prev_rank, 1,
MPI_COMM_WORLD);
67                 break;
68             }
69             printf("Process %d: Received BACKWARD counter = %d from %d\n",
world_rank, counter_backward, next_rank);
70             counter_backward++;
71             MPI_Send(&counter_backward, 1, MPI_INT, prev_rank, 0,
MPI_COMM_WORLD);
72
73             // FORWARD direction
74             MPI_Recv(&counter_forward, 1, MPI_INT, prev_rank, MPI_ANY_TAG,
MPI_COMM_WORLD, &status);
75             if (status.MPI_TAG == 1) {
76                 MPI_Send(&counter_forward, 1, MPI_INT, next_rank, 1,
MPI_COMM_WORLD);
77                 break;
78             }
79             printf("Process %d: Received FORWARD counter = %d from %d\n",
world_rank, counter_forward, prev_rank);
80             counter_forward++;
81             MPI_Send(&counter_forward, 1, MPI_INT, next_rank, 0,
MPI_COMM_WORLD);
82         }
83     }
84
85     printf("Process %d: Terminating\n", world_rank);
86     MPI_Finalize();
87     return 0;
88 }

```



```
(base) tazmeen@afroz:~/PDC$ mpicc Task4_b.c -o Task4b
(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task4b
Process 0: Starting bidirectional communication
Process 3: Received BACKWARD counter = 1 from 0
Process 2: Received BACKWARD counter = 2 from 3
Process 1: Received BACKWARD counter = 3 from 2
Process 1: Received FORWARD counter = 1 from 0
Process 0: Received BACKWARD counter = 4 from 1
Process 2: Received FORWARD counter = 2 from 1
Process 3: Received FORWARD counter = 3 from 2
Process 0: Received FORWARD counter = 4 from 3
Process 0: Completed cycle 1 of 2
Process 3: Received BACKWARD counter = 5 from 0
Process 0: Received BACKWARD counter = 8 from 1
Process 0: Received FORWARD counter = 8 from 3
Process 0: Completed cycle 2 of 2
Process 2: Received BACKWARD counter = 6 from 3
Process 2: Received FORWARD counter = 6 from 1
Process 1: Received BACKWARD counter = 7 from 2
Process 1: Received FORWARD counter = 5 from 0
Process 1: Terminating
Process 3: Received FORWARD counter = 7 from 2
Process 3: Terminating
Process 0: Terminating
Process 2: Terminating
(base) tazmeen@afroz:~/PDC$
```

Figure 5: Output of bi-directional implementation

Task 5: Performance Timing and Barriers

Problem Statement

1. Use MPI_Wtime to time the execution of Tasks 1 and 2.
2. Introduce MPI_Barrier to synchronize processes before timing starts and ends.

Report:

- Time taken for blocking vs non-blocking communication.
- Explain the overhead introduced by synchronization.

Implementation

```
1 #include <stdio.h>
2 #include <stdlib.h>
3 #include <mpi.h>
4
5 int main(int argc, char **argv) {
6     // rank - process id
7     // process_count - number of processes
8     int rank, process_count;
9     double start_time, end_time;
10
11     MPI_Init(&argc, &argv);
```

```

12 MPI_Comm_rank(MPI_COMM_WORLD, &rank);
13 MPI_Comm_size(MPI_COMM_WORLD, &process_count);
14
15 int array[16];
16 // Calculate the number of elements each worker process will handle
17 int elements_per_process = 16 / (process_count - 1);
18 int remaining_elements = 16 % (process_count - 1);
19
20 // Synchronize all processes before starting the timer
21 MPI_Barrier(MPI_COMM_WORLD);
22
23 // Start the timer
24 start_time = MPI_Wtime();
25
26 if(rank == 0) {
27     for(int i = 0; i < 16; i++) {
28         array[i] = i + 1;
29     }
30     printf("The original array is: ");
31     for(int i = 0; i < 16; i++) {
32         printf("%d ", array[i]);
33     }
34     printf("\n");
35
36     // Distribute the array to all worker processes
37     int start_index = 0;
38     for(int i = 1; i < process_count; i++) {
39         int count = elements_per_process;
40         if(i <= remaining_elements) {
41             count += 1; // Add 1 if there are remaining elements
42         }
43         MPI_Send(&array[start_index], count, MPI_INT, i, 0,
MPI_COMM_WORLD);
44         start_index += count;
45     }
46
47     // Collect results from all worker processes
48     start_index = 0;
49     for(int i = 1; i < process_count; i++) {
50         int count = elements_per_process;
51         if(i <= remaining_elements) {
52             count += 1; // Add 1 if there are remaining elements
53         }
54         MPI_Recv(&array[start_index], count, MPI_INT, i, 1,
MPI_COMM_WORLD, MPI_STATUS_IGNORE);
55         start_index += count;
56     }
57
58     // Print the results
59     printf("The squares are: ");
60     for(int i = 0; i < 16; i++) {
61         printf("%d ", array[i]);
62     }
63     printf("\n");

```

```

64     } else {
65         // Worker processes receive their portion of the array
66         int count = elements_per_process;
67         if(rank <= remaining_elements) {
68             count += 1;
69         }
70         int sub_array[count];
71         MPI_Recv(sub_array, count, MPI_INT, 0, 0, MPI_COMM_WORLD,
MPI_STATUS_IGNORE);
72
73         // Compute the square of each value
74         for(int i = 0; i < count; i++) {
75             sub_array[i] = sub_array[i] * sub_array[i];
76         }
77
78         // Send the results back to the root process
79         MPI_Send(sub_array, count, MPI_INT, 0, 1, MPI_COMM_WORLD);
80     }
81
82     // Synchronize all processes before stopping the timer
83     MPI_Barrier(MPI_COMM_WORLD);
84
85     // Stop the timer
86     end_time = MPI_Wtime();
87
88     // Print the execution time
89     if (rank == 0) {
90         printf("Task 1 (Blocking Communication) execution time: %f seconds
\n", end_time - start_time);
91     }
92
93     MPI_Finalize();
94     return 0;
95 }
96 #include <stdio.h>
97 #include <stdlib.h>
98 #include <mpi.h>
99
100 int main(int argc, char **argv) {
101     int rank, process_count;
102     double start_time, end_time;
103
104     MPI_Init(&argc, &argv);
105     MPI_Comm_rank(MPI_COMM_WORLD, &rank);
106     MPI_Comm_size(MPI_COMM_WORLD, &process_count);
107
108     int array[16];
109     int elements_per_process = 16 / (process_count - 1);
110     int remaining_elements = 16 % (process_count - 1);
111
112     // Synchronize all processes before starting the timer
113     MPI_Barrier(MPI_COMM_WORLD);
114
115     // Start the timer

```

```

116     start_time = MPI_Wtime();
117
118     if(rank == 0) {
119         for(int i = 0; i < 16; i++) {
120             array[i] = i + 1;
121         }
122         printf("The original array is: ");
123         for(int i = 0; i < 16; i++) {
124             printf("%d ", array[i]);
125         }
126         printf("\n");
127
128         // Arrays to manage asynchronous communication
129         MPI_Request send_requests[process_count - 1];
130         MPI_Request recv_requests[process_count - 1];
131
132         // Distribute the array to all worker processes
133         int start_index = 0;
134         for(int i = 1; i < process_count; i++) {
135             int count = elements_per_process;
136             if(i <= remaining_elements) {
137                 count += 1;
138             }
139             MPI_Isend(&array[start_index], count, MPI_INT, i, 0,
MPI_COMM_WORLD, &send_requests[i - 1]);
140             start_index += count;
141         }
142
143         // Collect results from all worker processes
144         start_index = 0;
145         for(int i = 1; i < process_count; i++) {
146             int count = elements_per_process;
147             if(i <= remaining_elements) {
148                 count += 1;
149             }
150             MPI_Irecv(&array[start_index], count, MPI_INT, i, 1,
MPI_COMM_WORLD, &recv_requests[i - 1]);
151             start_index += count;
152         }
153
154         // Wait for all sends and receives to complete
155         MPI_Waitall(process_count - 1, send_requests, MPI_STATUSES_IGNORE)
;
156         MPI_Waitall(process_count - 1, recv_requests, MPI_STATUSES_IGNORE)
;
157
158         // Print the results
159         printf("The squares are: ");
160         for(int i = 0; i < 16; i++) {
161             printf("%d ", array[i]);
162         }
163         printf("\n");
164     } else {
165         // Worker processes receive their portion of the array

```

```

166     int count = elements_per_process;
167     if(rank <= remaining_elements) {
168         count += 1;
169     }
170     int sub_array[count];
171     MPI_Request recv_request, send_request;
172
173     MPI_Irecv(sub_array, count, MPI_INT, 0, 0, MPI_COMM_WORLD, &
recv_request);
174     MPI_Wait(&recv_request, MPI_STATUS_IGNORE);
175
176     // Compute the square of each value
177     for(int i = 0; i < count; i++) {
178         sub_array[i] = sub_array[i] * sub_array[i];
179     }
180
181     // Send the results back to the root process
182     MPI_Isend(sub_array, count, MPI_INT, 0, 1, MPI_COMM_WORLD, &
send_request);
183     MPI_Wait(&send_request, MPI_STATUS_IGNORE);
184 }
185
186 // Synchronize all processes before stopping the timer
187 MPI_Barrier(MPI_COMM_WORLD);
188
189 // Stop the timer
190 end_time = MPI_Wtime();
191
192 // Print the execution time
193 if (rank == 0) {
194     printf("Task 2 (Non-blocking Communication) execution time: %f
seconds\n", end_time - start_time);
195 }
196
197 MPI_Finalize();
198 return 0;
199 }

```

```

(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task5a
The original array is: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
The squares are: 1 4 9 16 25 36 49 64 81 100 121 144 169 196 225 256
Task 1 (Blocking Communication) execution time: 0.000135 seconds
(base) tazmeen@afroz:~/PDC$ mpicc Task5_b.c -o Task5b
(base) tazmeen@afroz:~/PDC$ mpirun -np 4 ./Task5b
The original array is: 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
The squares are: 1 4 9 16 25 36 49 64 81 100 121 144 169 196 225 256
Task 2 (Non-blocking Communication) execution time: 0.000034 seconds
(base) tazmeen@afroz:~/PDC$

```

Figure 6: Output of Task 5 implementation showing timing results

Results and Analysis

Timing Results

- Blocking Communication: 0.000135 seconds
- Non-blocking Communication: 0.000034 seconds

Analysis

Non-blocking communication (0.000034s) is faster than blocking (0.000135s) because it enables parallel data transfer without waiting. MPI Barriers add synchronization overhead like network delays and load imbalance by forcing all processes to align before timing starts or ends, ensuring consistent results