Delft University of Technology

Introduction to High Performance Computing
WI4049TU

Lab Report

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General Remarks

This final Lab report includes the answers for the exercises (base grad denoted in paranthesis):

0. Introductory exercise (0.5)
1. Poisson solver (1.75)
2. Finite elements simulation (1.0)
3. Eigenvalue solution by Power Method on GPU (1.75)

The optional **shining points** (e.g., performance analysis, optimization, discussion, and clarifying figures) which yield further points are usually marked by a small blue heading in the text or an additional note is added under a figure or table. For example:
This is a shining point.

0 Introductory exercise

In the introductory lab session, we are taking a look at some basic features of MPI.
We start out very simple with a hello world program on two nodes.

Hello World

```c
#include "mpi.h"
#include <stdio.h>

int np, rank;

int main(int argc, char **argv)
{
  MPI_Init(&argc, &argv);
  MPI_Comm_size(MPI_COMM_WORLD, &np);
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);

  printf("Node %d of %d says: Hello world!\n", rank, np);

  MPI_Finalize();
  return 0;
}
```

This program can be compiled with the following command:

```
mpicc -o helloworld1.out helloworld1.c
```

And run with:

```
srun -n 2 -c 4 --mem-per-cpu=1GB  ./helloworld1.out
```

We get the following output:

```
Node 0 of 2 says: Hello world!
Node 1 of 2 says: Hello world!
```

From now on I'll skip the compilation and only mention on how many nodes the program is run and what the output is / interpretation of the output.

0.a) Ping Pong

I used the template to check how long `MPI_Send` and `MPI_Recv` take. The code can be found in the appendix for this section.

I've modified the printing a bit to make it easier to gather the information. Then I piped the program output into a textfile for further processing in python. I ran it first on one and then on two nodes as specified in the

assignment sheet. Opposed to the averaging over 5 send / receive pairs, I've done 1000 pairs. Furthmore I reran the whole programm 5 times to gather more data. All this data is shown in the following graph:

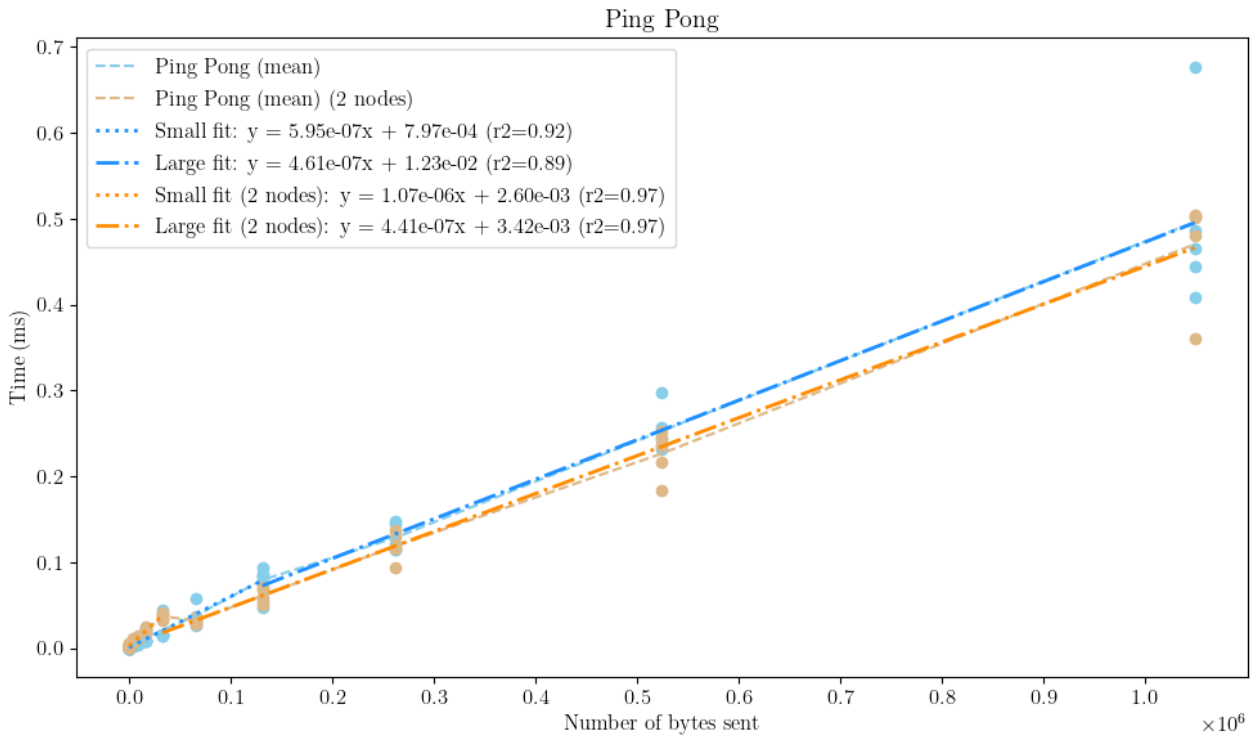


Figure 1: Ping Pong: Number of bytes sent vs. average time taken from 1000 pairs of send / receive. 5 runs shown for each size as scatter plot. Mean of these 5 runs shown as line. Blue small fit includes all data points up to 131072 bytes, blue large from there. Red small fit includes all data points up to 32768 bytes, red large from there.

As can be seen in the data and the fits, there are outliers especially for the larger data sizes.
For our runs we get the following fits and Rš values:

Run Type	**Data Size**	**Fit Equation**	**Rš Value**
Single Node	Small (<=131072)	$5.95 \times 10^{-7} \cdot x + 7.97 \times 10^{-4}$	0.92
Single Node	Large (>= 131072)	$4.61 \times 10^{-7} \cdot x + 1.23 \times 10^{-2}$	0.89
Two Node	Small (<=32768)	$1.07 \times 10^{-6} \cdot x + 2.60 \times 10^{-3}$	0.97
Two Node	Large (>=32768)	$4.41 \times 10^{-7} \cdot x + 3.42 \times 10^{-3}$	0.97

Table 1: Fit Equations and Rš Values for Single Node and Two Node Runs

Note: Each run was performed 5 times (for 1 and 2 nodes) to get a fit on the data and calculate a Rš value.
TODO: **Further analysis needed?**

Extra: Ping Pong with MPI_SendRecv

We do the same analysis for the changed program utilizing `MPI_SendRecv`. The code can be found in the appendix for this section.
We get the following graph from the measurements which were performed in the same way as for the previous program:

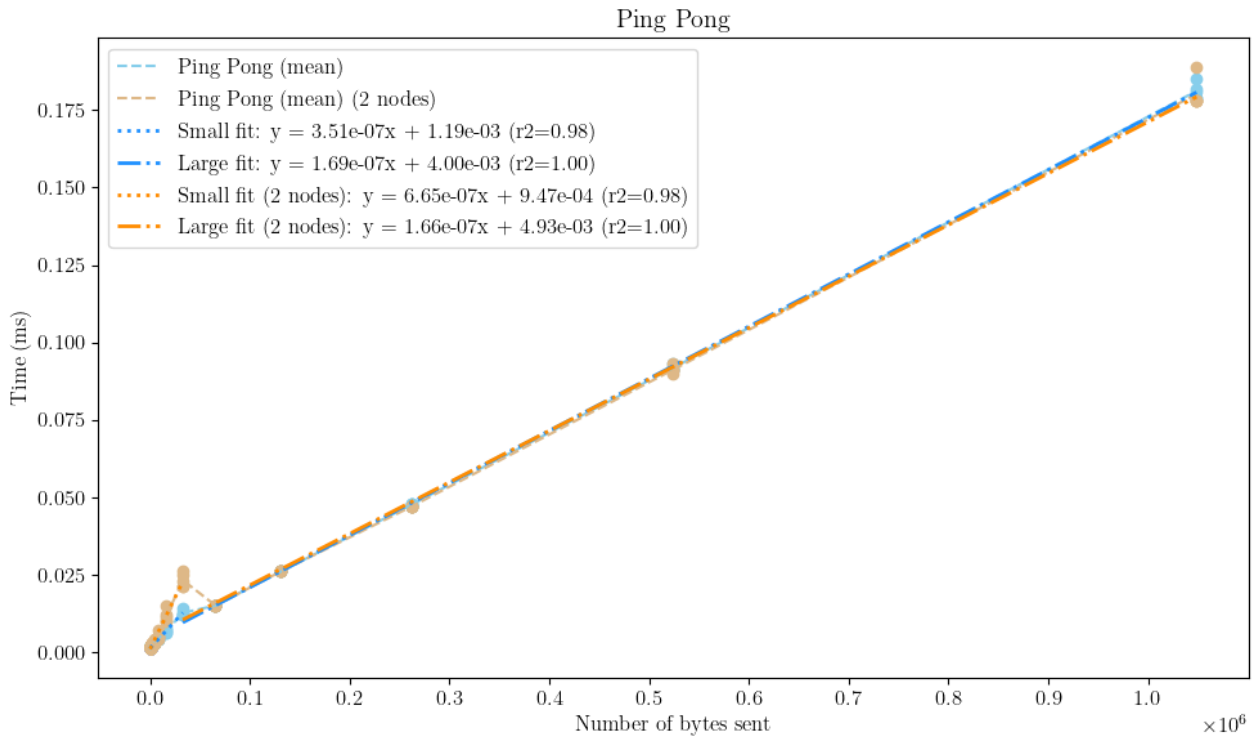


Figure 2: Ping Pong with MPI_SendRecv: Number of bytes sent vs. average time taken from 1000 pairs of send / receive. 5 runs shown for each size as scatter plot. Mean of these 5 runs shown as line. Blue small fit includes all data points up to 32768 bytes, blue large from there. Red small fit includes all data points up to 32768 bytes, red large from there.

We get the following fits and Rš values for the runs:

Run Type	**Data Size**	**Fit Equation**	**Rš Value**
Single Node	Small (<=32768)	$3.51 \times 10^{-7} \cdot x + 1.19 \times 10^{-3}$	0.98
Single Node	Large (>=32768)	$1.69 \times 10^{-7} \cdot x + 4.00 \times 10^{-3}$	1.00
Two Node	Small (<=32768)	$6.65 \times 10^{-7} \cdot x + 9.47 \times 10^{-4}$	0.98
Two Node	Large (>=32768)	$1.66 \times 10^{-7} \cdot x + 4.93 \times 10^{-3}$	1.00

Table 2: Fit Equations and Rš Values for Single Node and Two Node Runs

TODO: **Further analysis needed?**

0.b) MM-product

After an introduction of the matrix-matrix multiplication code in the next section, the measured speedups are discussed in the subsequent section.

Explanation of the code

For this excercise I've used the template provided in the assignment sheet as a base to develop my parallel implementation for a matrix-matrix multiplication. The code can be found in the appendix for this section.

The porgam can be run either in sequential (default) or parallel mode (parallel as a command line argument). For the sequential version, the code is practically unchanged and just refactored into a function for timing purposes. The parallel version is more complex and works as explained bellow:
First, rank 0 computes a sequential reference solution. Then rank 0 distributes the matrices in the following way in `splitwork`:

- Matrix A is split row-wise by dividing the number of rows by the number of nodes.
- The first worker (=rank 1) gets the most rows starting from row 0:
  $\texttt{total\_rows} - (\texttt{nr\_workers} - 1) \cdot \mathit{floor}(\frac{\texttt{total\_rows}}{\texttt{nr\_workers}})$.
- All other workers and the master (= rank 0) get the same number of rows: $\mathit{floor}(\frac{\texttt{total\_rows}}{\texttt{nr\_workers}})$.
- The master copies the corresponding rows of matrix A and the whole transposed matrix B* into a buffer (for details on `MM_input` buffer see bellow) for each worker and sends them off using `MPI_ISend`.
- The workers receive the data using `MPI_Recv` and then compute their part of the matrix product and send only the rows of the result matrix back to the master using `MPI_Send`.
- In the meanwhile the master computes its part of the matrix product.
- Using `MPI_Waitall` the master waits for all data to be sent to the workers and only afterwards calls `MPI_Recv` to gather the results from the workers.
- Finally all results are gathered by the master in the result matrix.

Assume we have a 5x5 matrix A and 2 workers (rank 1 and rank 2) and master (rank 0). The partitioning is done row-wise as follows:

Partitioning Example

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix} \rightarrow \begin{pmatrix} \text{Worker 1} \\ \text{Worker 1} \\ \text{Worker 1} \\ \text{Master} \\ \text{Master} \end{pmatrix}$$

- **Rank 0 (Master)**: Rows 4 and 5 (last two rows)
- **Rank 1 (Worker 1)**: Rows 1 to 3 (first three rows) - Worker 1 always gets the most rows

This partitioning can be visually represented as:

$$\text{Master (rank 0):} \begin{pmatrix} a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{pmatrix}$$

$$\text{Worker 1 (rank 1):} \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \end{pmatrix}$$

Each worker computes its part of the matrix product, and the master gathers the results at the end and compiles them into the final matrix.
The `MM_input` buffer is used to store the rows of matrix A and the whole matrix B for each worker. It is implemented using a simple struct:

```
typedef struct MM_input {
    size_t rows;
    double *a;
    double *b;
} MM_input;
```

***[Optimization] Note on transposed matrix B:** It is usually beneficial from a cache perspective to index arrays sequentially or in a row-major order. However, in the matrix-matrix multiplication, we access the elements of matrix B in a column-wise order. This leads to cache misses and is not optimal. To mitigate this, we can transpose matrix B and then access it in a row-wise order. This is done in the code by the master before sending the data to the workers.

Discussion of the speedups

The code was run on Delft's cluster with 1, 2, 4, 8, 16, 24, 32, 48, and 64 nodes. For the experiments the matrix size of A and B was set to 2000×2000. This means that the program has to evaluate 2000 multiplications and 1999 additions for each element of the resulting matrix C. In total this results in $\approx 2000^3 = 8 \times 10^9$ operations. The command looked similar to the following for the different node counts:

```
srun -n 48 --mem-per-cpu=4GB --time=00:02:00 ./MM.out parallel
```

For this experiment, the execution time was measured and the speedup was calculated. The results are shown in Table 3 and Figure 3.

CPU Count	Execution Time / s	Approx. Speedup
1	47.11	1.0
2	10.26	4.6
4	10.30	4.6
8	5.20	9.1
16	2.97	15.9
24	2.54	18.5
32	2.29	20.6
48	2.98	15.8
64	1.72	27.4

Table 3: Execution Time vs CPU Count

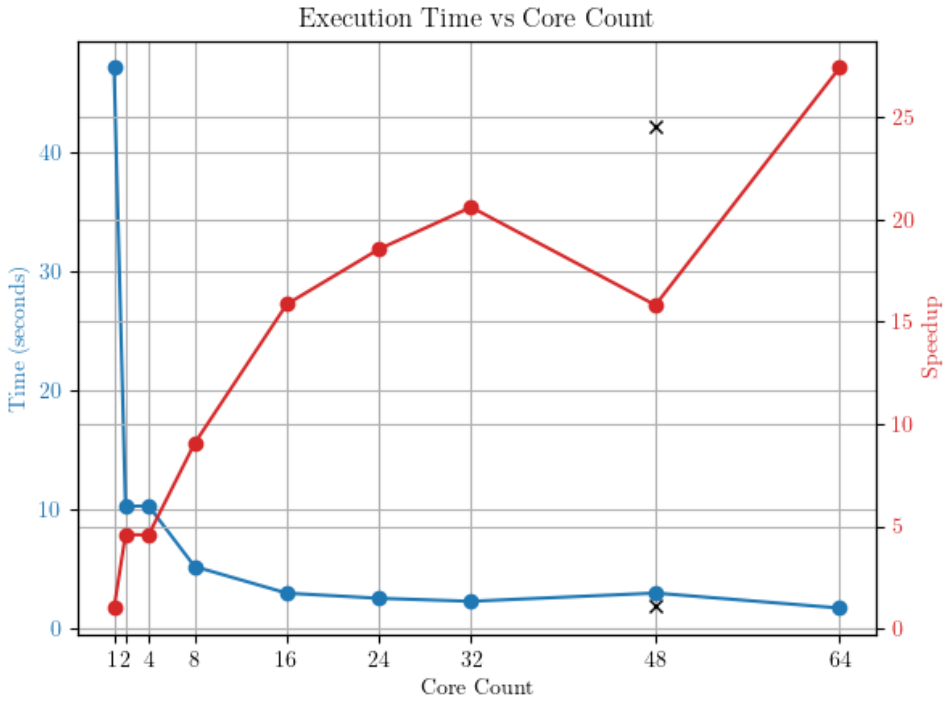


Figure 3: Speedup vs CPU Count
Black × marks the average of the rerun for $n = 48$.

Note: The speedup is calculated as $S = \frac{T_1}{T_p}$, where T_1 is the execution time on 1 node and T_p is the execution time on p nodes.

Discussion:
As one can cleary discern from the data in Table 3 and Figure 3, the speedup increases with the number of nodes (with the exception of $n = 48$). This is expected as the more nodes we have, the more work can be done in

parallel. However, the speedup is not linear. This is due to the overhead of communication between the nodes. The more nodes we have, the more communication is needed, and this overhead increases. This is especially visible in the data for $n = 48$. Here the speedup is lower than for $n = 32$. For this run the communication didn't went as smooth as for the other runs. This can potentially be attributed to the fact that one (or more) of the nodes or the network was under heavy load during this task.
[Further investigation] After observing this slower speed for the $n = 48$, I reran the tests multiple times and got a runtime of around $1.9s$ which was to be expected initially. Therefore, this one run is an odd one out, most likely due to the reasons mentioned above! I've also added the averaged data of the reruns as a datapoint in Figure 3.
Another interesting fact can be seen when comparing the time taken for $n = 1$ and $n = 2$. They don't at all scale with the expected factor of 2. This is could be due to the fact, that the resource management system prefers runs with multiple nodes instead of a single node (= sequential).

Additional notes: The flag `-mem-per-cpu=<#>GB` was set depending on the number of nodes used. For 1-24 nodes 8GB was used, for 32-48 nodes 4GB, and for 64 nodes 3GB. This had to be done to comply with QOS policy on the cluster.
TODO: **Data locality?**

1 Poisson solver

In this section of the lab report, we will dicuss a prallel implementation of the Poisson solver. The Poisson solver is a numerical method used to solve the Poisson equation, which is a partial differential equation that is useful in many areas of physics.
Note: For local testing and development I'll run the code with `mpirun` instead of the `srun` command on the cluster.

1.1 Building a parallel Poisson solver

For the first part of the exercise we follow the steps lined out in the assignment sheet. I'll comment on the steps 1 through 10 and related questions bellow. The finished implementation can be found in the appendix for this section.

1. **Step:** After adding MPI_Init and MPI_Finalize, we can run the program with multiple processes. We can see that the program runs with 4 processes in Figure 4 via the quadrupeled output.

```
etschgi1@Deep-Thought:~/REPOS/HPC/01_lab1/src$ mpirun -np 4 ./mpi.out
 Number of iterations : 2355
 Number of iterations : 2355
 Number of iterations : 2355
 Elapsed processortime:       0.133189 s
 Number of iterations : 2355
 Elapsed processortime:       0.134150 s
 Elapsed processortime:       0.134474 s
 Elapsed processortime:       0.135356 s
```

Figure 4: MPI_Poisson after Step 1 - Running with 4 processes

2. **Step:** To see which process is doing what, I included the rank of the process for the print statements as shown in Figure 5.

```
etschgi1@Deep-Thought:~/REPOS/HPC/02_lab1/src$ mpirun -np 4 ./mpi.out
 (0) Number of iterations : 2355
 (2) Number of iterations : 2355
 (0) Elapsed processortime:       0.135963 s
 (2) Elapsed processortime:       0.137101 s
 (3) Number of iterations : 2355
 (3) Elapsed processortime:       0.139614 s
 (1) Number of iterations : 2355
 (1) Elapsed processortime:       0.142026 s
```

Figure 5: MPI_Poisson after Step 2 - Running with 4 processes

3. **Step:** Next we define `wtime` as a global double and replace the four utility timing functions with the ones given on Brightspace. A quick verification as shown in Figure 6 shows that the program still runs as expected.

```
etschgi1@Deep-Thought:~/REPOS/HPC/02_lab1/src$ mpirun -np 4 ./mpi.out
 (3) Number of iterations : 2355
 (1) Number of iterations : 2355
 (3) Elapsed Wtime       0.134918 s ( 98.5% CPU)
 (1) Elapsed Wtime       0.134459 s ( 98.5% CPU)
 (0) Number of iterations : 2355
 (2) Number of iterations : 2355
 (0) Elapsed Wtime       0.138669 s ( 98.5% CPU)
 (2) Elapsed Wtime       0.138910 s ( 98.5% CPU)
```

Figure 6: MPI_Poisson after Step 3 - Running with 4 processes

4. **Step:** Next we check if two processes indeed give the same output. Both need 2355 iterations to converge and the `diff` command returned no output, which means that the files content is identical.
5. **Step:** Now only the process with rank 0 will read data from files and subsequently broadcast it to the others. Testing this again with 2 processes, we see an empty diff of the output files and the same number of iterations needed to converge.

6. **Step:** We create a cartesian grid of processes using `MPI_Cart_create` and use `MPI_Cart_shift` to find the neighbors of each process. We can see that the neighbors are correctly identified in Figure 7.

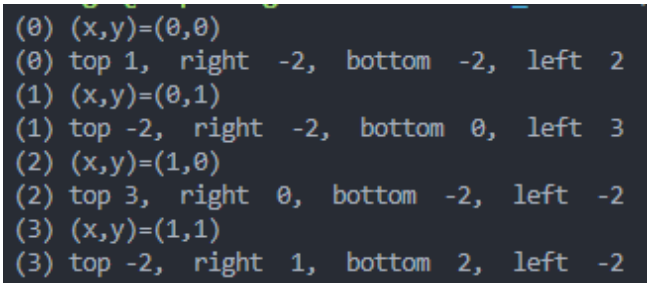
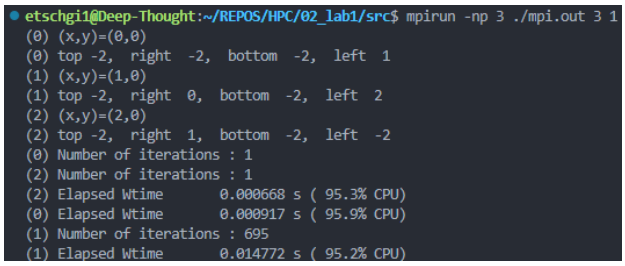


Figure 7: MPI_Poisson after Step 6 - Running with 4 processes on a 2x2 grid

When there is no neighbor in a certain direction, -2 (or `MPI_PROC_NULL`) is returned.

7. **Step:** We overhaul the setup to get a proper local grid for each process. Furthermore, we only save the relevant source fields in the local grid for each process.
With for instance 3 processes you should see that 1 or 2 processes do not do any iteration. Do you understand why?
If we have a look at the input file we see that there are only 3 source fields in the grid. This means that the process that does not have a source field in its local grid will not do any iterations (or only 1). Therefore, if we have 3 processes and the distribution of source fields as given in the input file only 1 process will do iterations if processes are ordered in x-direction and 2 if ordered in y-direction. From this we can conclude that indeed all processes have different local grids and perform different calculations.



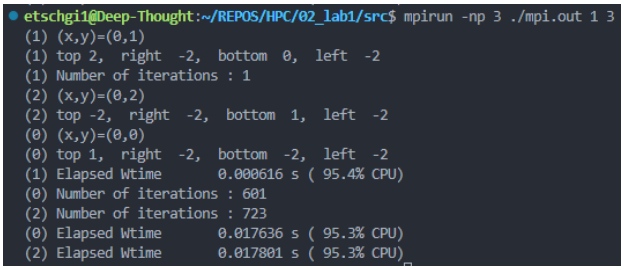


Figure 8: MPI_Poisson after Step 7 - Running with 3 processes on a 3x1 (left) vs. 1x3 (right) grid
For the 3x1 grid, only rank 1 does iterations (> 1), for the 1x3 grid, ranks 0 and 2 do iterations (> 1).

8. **Step:** After defining and commiting two special datatypes for vertical and horizontal communication, we setup the communication logic to exchange the boundary values between the processes. We call our `Exchange_Borders` function after each iteration (for both red / black grid points). Now we face the problem in which some processes may stop instantly (no source in their local grid). They will not supply any data to their neighbors, which will cause the program to hang. We shall fix this in the next step.

9. **Step:** Finally we need to implement the logic to check for convergence (in a global sense). We do this by using a `MPI_Allreduce` call with the `MPI_MAX` operation. This way we aggregate all deltas and choose the biggest one for the global delta which we use in the while-loop-condition to check for convergence. We can see that the program now runs as expected in Figure 9.

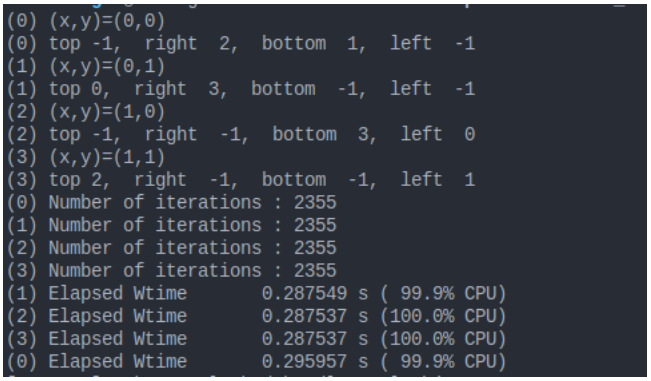


Figure 9: MPI_Poisson after Step 9 - Running with 4 processes on a 2x2 grid

Note that this run in Figure 9 was done with another pc and another MPI implementation. Therefore, we see -1 for cells without a neighbor! However, other than that cosmetic difference it has no impact on the programm.

10. **Step:** Now we only have to fix two remaining things. First we have to make sure that each process uses the right global coordinates for the output file in the end. Therefore, we change the function a bit to include the specific x-/y-offset for each processor. The second thing is the potential problem, that different processors might start with different (red/black) parities. In order to accomplish a global parity we simply have to change the calculation in the if in `Do_Step` from

```
1         if ((x + y) % 2 == parity && source[x][y] != 1)
```

to

```
1         if ((x + offset[X_DIR] + y + offset[Y_DIR]) % 2 == parity && source[x][y] != 1)
```

this guarantees that during a given iteration all processors are using the same parity.

This just leaves one question open: Are the results acutally the same?
Checking the output files of the MPI-implementation with the sequential reference indeed shows identical numerical values for the calculated points. Furthermore, the needed iterationcount is also identical which isn't a big surprise, given that the two programms perform the exact same calculation steps.

1.2 Exercises, modifications, and performance aspects

For this subsection we'll define the following shorthand notation:

n:	the number of iterations
g:	gridsize
t:	time needed in seconds
pt:	processor topology in form pxy, where:
p:	number of processors used
x:	number of processors in x-direction
y:	number of processors in y-direction

Table 4: Notation for this section

$pt = 414$ means 4 processors in a 1×4 topology.

2 Finite elements simulation

3 Eigenvalue solution by Power Method on GPU

Appendix - Introductory exercise

The following code was used for the ping pong task:

```
#include <stdio.h>
#include <stdlib.h>
#include <mpi.h>

// Maximum array size 2^20= 1048576 elements
#define MAX_EXPONENT 20
#define MAX_ARRAY_SIZE (1<<MAX_EXPONENT)
#define SAMPLE_COUNT 1000

int main(int argc, char **argv)
{
    // Variables for the process rank and number of processes
    int myRank, numProcs, i;
    MPI_Status status;

    // Initialize MPI, find out MPI communicator size and process rank
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numProcs);
    MPI_Comm_rank(MPI_COMM_WORLD, &myRank);


    int *myArray = (int *)malloc(sizeof(int)*MAX_ARRAY_SIZE);
    if (myArray == NULL)
    {
        printf("Not enough memory\n");
        exit(1);
    }
    // Initialize myArray
    for (i=0; i<MAX_ARRAY_SIZE; i++)
        myArray[i]=1;

    int number_of_elements_to_send;
    int number_of_elements_received;

    // PART C
    if (numProcs < 2)
    {
        printf("Error: Run the program with at least 2 MPI tasks!\n");
        MPI_Abort(MPI_COMM_WORLD, 1);
    }
    double startTime, endTime;

    // TODO: Use a loop to vary the message size
    for (size_t j = 0; j <= MAX_EXPONENT; j++)
    {
        number_of_elements_to_send = 1<<j;
        if (myRank == 0)
        {
            myArray[0]=myArray[1]+1; // activate in cache (avoids possible delay when sending
    the 1st element)
            startTime = MPI_Wtime();
            for (i=0; i<SAMPLE_COUNT; i++)
            {
                MPI_Send(myArray, number_of_elements_to_send, MPI_INT, 1, 0,
                    MPI_COMM_WORLD);
                MPI_Probe(MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &status);
                MPI_Get_count(&status, MPI_INT, &number_of_elements_received);

                MPI_Recv(myArray, number_of_elements_received, MPI_INT, 1, 0,
                    MPI_COMM_WORLD, MPI_STATUS_IGNORE);
            } // end of for-loop

            endTime = MPI_Wtime();
            printf("Rank %2.1i: Received %i elements: Ping Pong took %f seconds\n", myRank,
    number_of_elements_received,(endTime - startTime)/(2*SAMPLE_COUNT));
        }
        else if (myRank == 1)
        {
            // Probe message in order to obtain the amount of data
            MPI_Probe(MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &status);
```

```
            MPI_Get_count(&status, MPI_INT, &number_of_elements_received);

            for (i=0; i<SAMPLE_COUNT; i++)
            {
                MPI_Recv(myArray, number_of_elements_received, MPI_INT, 0, 0,
                MPI_COMM_WORLD, MPI_STATUS_IGNORE);
                MPI_Send(myArray, number_of_elements_to_send, MPI_INT, 0, 0,
                MPI_COMM_WORLD);
            } // end of for-loop
        }
    }

    // Finalize MPI
    MPI_Finalize();

    return 0;
}
```

For the bonus task, the following code was used:

```
#include <stdio.h>
#include <stdlib.h>
#include <mpi.h>

// Maximum array size 2^20= 1048576 elements
#define MAX_EXPONENT 20
#define MAX_ARRAY_SIZE (1<<MAX_EXPONENT)
#define SAMPLE_COUNT 1000

int main(int argc, char **argv)
{
    // Variables for the process rank and number of processes
    int myRank, numProcs, i;
    MPI_Status status;

    // Initialize MPI, find out MPI communicator size and process rank
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &numProcs);
    MPI_Comm_rank(MPI_COMM_WORLD, &myRank);


    int *myArray = (int *)malloc(sizeof(int)*MAX_ARRAY_SIZE);
    if (myArray == NULL)
    {
        printf("Not enough memory\n");
        exit(1);
    }
    // Initialize myArray
    for (i=0; i<MAX_ARRAY_SIZE; i++)
        myArray[i]=1;

    int number_of_elements_to_send;
    int number_of_elements_received;

    // PART C
    if (numProcs < 2)
    {
        printf("Error: Run the program with at least 2 MPI tasks!\n");
        MPI_Abort(MPI_COMM_WORLD, 1);
    }
    double startTime, endTime;

    // TODO: Use a loop to vary the message size
    for (size_t j = 0; j <= MAX_EXPONENT; j++)
    {
        number_of_elements_to_send = 1<<j;
        if (myRank == 0)
        {
            myArray[0]=myArray[1]+1; // activate in cache (avoids possible delay when sending
    the 1st element)
            startTime = MPI_Wtime();
            for (i=0; i<SAMPLE_COUNT; i++)
            {
                MPI_Sendrecv(myArray, number_of_elements_to_send, MPI_INT, 1,0,myArray,
```

```
    number_of_elements_to_send, MPI_INT, 1, 0, MPI_COMM_WORLD, &status);
54              }
55
56              endTime = MPI_Wtime();
57              printf("Rank %2.1i: Received %i elements: Ping Pong took %f seconds\n", myRank,
    number_of_elements_to_send,(endTime - startTime)/(2*SAMPLE_COUNT));
58          }
59          else if (myRank == 1)
60          {
61              for (i=0; i<SAMPLE_COUNT; i++)
62              {
63                  MPI_Sendrecv(myArray, number_of_elements_to_send, MPI_INT, 0,0,myArray,
    number_of_elements_to_send, MPI_INT, 0, 0, MPI_COMM_WORLD, &status);
64              }
65          }
66      }
67
68      // Finalize MPI
69      MPI_Finalize();
70
71      return 0;
72  }
```

The matrix multiplication used the following code:

```
1  /******************************************************************************
2   * FILE: mm.c
3   * DESCRIPTION:
4   *   This program calculates the product of matrix a[nra][nca] and b[nca][ncb],
5   *   the result is stored in matrix c[nra][ncb].
6   *   The max dimension of the matrix is constraint with static array
7   *declaration, for a larger matrix you may consider dynamic allocation of the
8   *arrays, but it makes a parallel code much more complicated (think of
9   *communication), so this is only optional.
10  *
11  ******************************************************************************/
12
13 #include <math.h>
14 #include <mpi.h>
15 #include <stdbool.h>
16 #include <stdio.h>
17 #include <stdlib.h>
18 #include <string.h>
19
20 #define NRA 2000 /* number of rows in matrix A */
21 #define NCA 2000 /* number of columns in matrix A */
22 #define NCB 2000 /* number of columns in matrix B */
23 // #define N 1000
24 #define EPS 1e-9
25 #define SIZE_OF_B NCA*NCB*sizeof(double)
26
27 bool eps_equal(double a, double b) { return fabs(a - b) < EPS; }
28
29 void print_flattened_matrix(double *matrix, size_t rows, size_t cols, int rank) {
30     printf("[%d]\n", rank);
31     for (size_t i = 0; i < rows; i++) {
32         for (size_t j = 0; j < cols; j++) {
33             printf("%10.2f ", matrix[i * cols + j]);  // Accessing element in the 1D array
34         }
35         printf("\n");  // Newline after each row
36     }
37 }
38
39 int checkResult(double *truth, double *test, size_t Nr_col, size_t Nr_rows) {
40     for (size_t i = 0; i < Nr_rows; ++i) {
41         for (size_t j = 0; j < Nr_col; ++j) {
42             size_t index = i * Nr_col + j;
43             if (!eps_equal(truth[index], test[index])) {
44                 return 1;
45             }
46         }
47     }
48     return 0;
49 }
```

```
50
51 typedef struct {
52     size_t rows;
53     double *a;
54     double *b;
55 } MM_input;
56
57 char* getbuffer(MM_input *in, size_t size_of_buffer){
58     char* buffer = (char*)malloc(size_of_buffer * sizeof(char));
59     if (buffer == 0)
60     {
61         printf("Buffer couldn't be allocated.");
62         return NULL;
63     }
64     size_t offset = 0;
65     memcpy(buffer + offset, &in->rows, sizeof(size_t));
66     offset += sizeof(size_t);
67     size_t matrix_size = in->rows * NCA * sizeof(double);
68     memcpy(buffer + offset, in->a, matrix_size);
69     offset += matrix_size;
70     memcpy(buffer + offset, in->b, NCA*NCB*sizeof(double));
71     return buffer;
72 }
73
74 MM_input* readbuffer(char* buffer, size_t size_of_buffer){
75     MM_input *mm = (MM_input*)malloc(sizeof(MM_input));
76
77     mm->rows = ((size_t*)buffer)[0];
78     size_t offset = sizeof(size_t);
79     size_t matrix_size =  mm->rows * NCA;
80     mm->a = (double*)malloc(sizeof(double)*matrix_size);
81     mm->b = (double*)malloc(sizeof(double)*matrix_size);
82     memcpy(mm->a, &(buffer[offset]), matrix_size);
83     offset += matrix_size;
84     memcpy(mm->b, &(buffer[offset]), NCA*NCB*sizeof(double));
85     free(buffer);
86     return mm;
87 }
88
89
90 void setupMatrices(double (*a)[NCA], double (*b)[NCB], double (*c)[NCB]){
91     for (size_t i = 0; i < NRA; i++) {
92         for (size_t j = 0; j < NCA; j++) {
93             a[i][j] = i + j;
94         }
95     }
96
97     for (size_t i = 0; i < NCA; i++) {
98         for (size_t j = 0; j < NCB; j++) {
99             b[i][j] = i * j;
100        }
101    }
102
103    for (size_t i = 0; i < NRA; i++) {
104        for (size_t j = 0; j < NCB; j++) {
105            c[i][j] = 0;
106        }
107    }
108 }
109
110 double multsum(double* a,double* b_transposed, size_t size){
111     double acc = 0;
112     for (size_t i = 0; i < size; i++)
113     {
114         acc += a[i]*b_transposed[i];
115     }
116     return acc;
117 }
118
119 double productSequential(double *res) {
120     // dynamically allocate to not run into stack overflow - usually stacks are
121     // 8192 bytes big -> 1024 doubles but we have 1 Mio. per matrix
122     double(*a)[NCA] = malloc(sizeof(double) * NRA * NCA);
```

```
123     double(*b)[NCB] = malloc(sizeof(double) * NCA * NCB);
124     double(*c)[NCB] = malloc(sizeof(double) * NRA * NCB);
125 
126     /*** Initialize matrices ***/
127     setupMatrices(a,b,c);
128 
129     /* Parallelize the computation of the following matrix-matrix
130    multiplication. How to partition and distribute the initial matrices, the
131    work, and collecting final results.
132     */
133     // multiply
134     double start = MPI_Wtime();
135     for (size_t i = 0; i < NRA; i++) {
136         for (size_t j = 0; j < NCB; j++) {
137             for (size_t k = 0; k < NCA; k++) {
138                 res[i * NCB + j] += a[i][k] * b[k][j];
139             }
140         }
141     }
142     /*  perform time measurement. Always check the correctness of the parallel
143        results by printing a few values of c[i][j] and compare with the
144        sequential output.
145     */
146     double time = MPI_Wtime()-start;
147     free(a);
148     free(b);
149     free(c);
150     return time;
151 }
152 
153 double splitwork(double* res, size_t num_workers){
154     if (num_workers == 0) // sadly noone will help me :((
155     {
156         printf("Run sequential!\n");
157         return productSequential(res);
158     }
159 
160     double(*a)[NCA] = malloc(sizeof(double) * NRA * NCA);
161     double(*b)[NCB] = malloc(sizeof(double) * NCA * NCB);
162     double(*c)[NCB] = malloc(sizeof(double) * NRA * NCB);
163     // Transpose matrix b to make accessing columns easier - in row major way - better cache
    performance
164     setupMatrices(a,b,c);
165 
166     double start_time = MPI_Wtime();
167     double (*b_transposed)[NCA] = malloc(sizeof(double) * NCA * NCB);
168     for (size_t i = 0; i < NCA; i++) {
169         for (size_t j = 0; j < NCB; j++) {
170             b_transposed[j][i] = b[i][j];
171         }
172     }
173 
174     /*** Initialize matrices ***/
175     // given number of workers I'll split
176     size_t rows_per_worker = NRA / (num_workers+1); //takes corresponding columns from other
    matrix
177     printf("rows per worker: %zu\n", rows_per_worker);
178     size_t row_end_first = NRA - rows_per_worker*num_workers;
179     printf("first gets most: %zu\n", row_end_first);
180 
181     //setup requests
182     MPI_Request requests[num_workers];
183     MM_input *data_first = (MM_input*)malloc(sizeof(MM_input));
184     data_first->rows = row_end_first;
185     data_first->a = (double*)a; //they both start of with no offset!
186     data_first->b = (double*)b_transposed;
187     size_t total_size = sizeof(size_t) + (data_first->rows * NCA)*sizeof(double)+SIZE_OF_B;
188     char* buffer = getbuffer(data_first, total_size);    //first one
189 
190     // Tag is just nr-cpu -1
191     MPI_Isend(buffer, total_size, MPI_CHAR, 1, 0,MPI_COMM_WORLD, &requests[0]);
192     free(data_first);
193     total_size = sizeof(size_t) + (rows_per_worker * NCA)*sizeof(double) + SIZE_OF_B; //size
```

```
    is the same for all other - just compute once!
    size_t i;
    for (i = 0; i < (num_workers-1); ++i)
    {
        MM_input *data = (MM_input*)malloc(sizeof(MM_input));
        data->rows = rows_per_worker;
        data->a = (double*)(a + (row_end_first + rows_per_worker*i));
        data->b = (double*)(b_transposed); // send everyting - all needed
        buffer = getbuffer(data, total_size);
        printf("nr_worker - %zu\n", i);
        MPI_Isend(buffer, total_size, MPI_CHAR, i+2, i+1,MPI_COMM_WORLD, &requests[i+1]);
        free(data);
    }
    double* my_a = (double*)(a + (row_end_first + rows_per_worker*i));

    //I multiply the rest
    size_t offset = 0;
    for (size_t row = (NRA-rows_per_worker); row < NRA; row++)
    {
        for (size_t col = 0; col < NCB; col++)
        {
            res[row * NCB + col] = multsum(my_a+offset, (((double*)b_transposed)+col*NCA), NCA
    );
        }
        offset += NCA;
    }
    printf("My c: \n");
    //wait for rest
    MPI_Status stats[num_workers];
    if(MPI_Waitall(num_workers, requests, stats) == MPI_ERR_IN_STATUS){
        printf("Communication failed!!! - abort\n");
    }
    printf(">>>Everything sent and recieved\n");

    // reviece rest
    size_t buf_size = sizeof(double)*row_end_first*NCB;
    double* revbuf;
    offset = 0;
    for (size_t worker = 0; worker < num_workers; worker++)
    {
        revbuf = (double*)malloc(buf_size); //first gets largest buffer
        MPI_Recv(revbuf, buf_size/sizeof(double), MPI_DOUBLE, worker+1, worker, MPI_COMM_WORLD
    ,&stats[worker]);
        memcpy(&res[offset/sizeof(double)], revbuf, buf_size);
        free(revbuf);
        offset += buf_size;
        buf_size = sizeof(double)*rows_per_worker*NCB;
    }
    double time = MPI_Wtime()-start_time;
    //free all pointers!
    free(a);
    free(b);
    free(b_transposed);
    free(c);
    return time;
}



double work(int rank, size_t num_workers){
    size_t rows_per_worker = NRA / (num_workers+1);
    char* buffer;
    MPI_Status status;
    if (rank == 1) // first always get's most work
    {
        rows_per_worker = NRA - rows_per_worker*num_workers;
    }
    size_t size_of_meta = sizeof(size_t);
    size_t size_of_a = sizeof(double)*rows_per_worker*NCA;
    size_t buffersize = size_of_meta+size_of_a + SIZE_OF_B;
    buffer = (char*)malloc(buffersize);

    MPI_Recv(buffer, buffersize, MPI_CHAR, 0, rank-1, MPI_COMM_WORLD, &status);
```

```
264     double start = MPI_Wtime();
265     int count;
266     MPI_Get_count(&status, MPI_CHAR, &count);
267     printf("I'm rank %d and I got %d bytes (%ld doubles) of data from %d with tag %d.\n", rank
        , count, (count-sizeof(size_t))/sizeof(double), status.MPI_SOURCE, status.MPI_TAG);
268
269     MM_input *mm = (MM_input*)malloc(sizeof(MM_input));
270     mm->a = (double*)&buffer[size_of_meta];
271     mm->b = (double*)&buffer[size_of_meta+size_of_a];
272
273     double *res =(double*)malloc(sizeof(double)*rows_per_worker*NCB);
274
275     size_t offset = 0;
276     for (size_t row = 0; row < rows_per_worker; row++)
277     {
278         for (size_t col = 0; col < NCB; col++)
279         {
280             res[row * NCB + col] = multsum(mm->a+offset, (((double*)mm->b)+col*NCA), NCA);
281         }
282         offset += NCA;
283     }
284     MPI_Send(res, rows_per_worker*NCB, MPI_DOUBLE, 0,rank-1, MPI_COMM_WORLD);
285     printf("[%d] sent res home\n",rank);
286     free(res);
287     return MPI_Wtime() - start;
288 }
289
290 int main(int argc, char *argv[]) {
291     int tid, nthreads;
292     /* for simplicity, set NRA=NCA=NCB=N  */
293     // Initialize MPI, find out MPI communicator size and process rank
294     int myRank, numProcs;
295     MPI_Status status;
296     MPI_Init(&argc, &argv);
297     MPI_Comm_size(MPI_COMM_WORLD, &numProcs);
298     MPI_Comm_rank(MPI_COMM_WORLD, &myRank);
299     int num_Workers = numProcs-1;
300     if (argc > 1 && strcmp(argv[1], "parallel") == 0) {
301         // Variables for the process rank and number of processes
302        if (myRank == 0) {
303             printf("Run parallel!\n");
304             double *truth = malloc(sizeof(double) * NRA * NCB);
305             double time = productSequential(truth);
306             printf("Computed reference results in %.6f s\n", time);
307             printf("Hello from master! - I have %d workers!\n", num_Workers);
308             // send out work
309             double *res = malloc(sizeof(double)*NRA*NCB);
310             time = splitwork(res, num_Workers);
311             if (checkResult(res, truth, NCB, NRA)) {
312                 printf("Matrices do not match!!!\n");
313                 return 1;
314             }
315             printf("Matrices match (parallel [eps %.10f])! - took: %.6f s\n", EPS, time);
316             free(truth);
317             free(res);
318         } else {
319             double time = work(myRank, num_Workers);
320             printf("Worker bee %d took %.6f s (after recv) for my work\n", myRank, time);
321         }
322
323     } else  // run sequantial
324     {
325         printf("Run sequantial!\n");
326         double *res = malloc(sizeof(double) * NRA * NCB);
327         double time = productSequential(res);
328         if (checkResult(res, res, NCB, NRA)) {
329             printf("Matrices do not match!!!\n");
330             return 1;
331         }
332         printf("Matrices match (sequantial-trivial)! - took: %.6f s\n", time);
333         free(res);
334     }
335
```

```
    MPI_Finalize();
    return 0;
}
```

Appendix - Poisson solver

The parallel Poisson solver used the following code:

```
/*
 * MPI_Poisson.c
 * 2D Poison equation solver (parallel version)
 */

#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <time.h>
#include <mpi.h>
#include <assert.h>

#define DEBUG 0

#define max(a,b) ((a)>(b)?a:b)

enum
{
    X_DIR, Y_DIR
};

/* global variables */
int gridsize[2];
double precision_goal;    /* precision_goal of solution */
int max_iter;     /* maximum number of iterations alowed */
int P; //total number of processes
int P_grid[2]; // process grid dimensions
MPI_Comm grid_comm; //grid communicator
MPI_Status status;

/* process specific globals*/
int proc_rank;
double wtime;
int proc_coord[2]; // coords of current process in processgrid
int proc_top, proc_right, proc_bottom, proc_left; // ranks of neighboring procs
// step 7
int offset[2] = {0,0};
// step 8
MPI_Datatype border_type[2];

/* benchmark related variables */
clock_t ticks;      /* number of systemticks */
int timer_on = 0;   /* is timer running? */

/* local grid related variables */
double **phi;     /* grid */
int **source;     /* TRUE if subgrid element is a source */
int dim[2];     /* grid dimensions */

void Setup_Grid();
double Do_Step(int parity);
void Solve();
void Write_Grid();
void Clean_Up();
void Debug(char *mesg, int terminate);
void start_timer();
void resume_timer();
void stop_timer();
void print_timer();

void start_timer()
{
    if (!timer_on){
        MPI_Barrier(grid_comm);
```

```
        ticks = clock();
        wtime = MPI_Wtime();
        timer_on = 1;
    }
}

void resume_timer()
{
    if (!timer_on){
        ticks = clock()  -  ticks;
        wtime = MPI_Wtime() - wtime;
        timer_on = 1;
    }
}

void stop_timer()
{
    if (timer_on){
        ticks = clock()  -  ticks;
        wtime = MPI_Wtime() - wtime;
        timer_on = 0;
    }
}

void print_timer()
{
    if (timer_on){
        stop_timer();
        printf("(%i) Elapsed Wtime %14.6f s (%5.1f%% CPU)\n", proc_rank, wtime, 100.0 * ticks
    * (1.0 / CLOCKS_PER_SEC) / wtime);
        resume_timer();
    }
    else{
        printf("(%i) Elapsed Wtime %14.6f s (%5.1f%% CPU)\n", proc_rank, wtime, 100.0 * ticks
    * (1.0 / CLOCKS_PER_SEC) / wtime);
    }
}

void Debug(char *mesg, int terminate)
{
    if (DEBUG || terminate){
        printf("%s\n", mesg);
    }
    if (terminate){
        exit(1);
    }
}

void Setup_Proc_Grid(int argc, char **argv){
    int wrap_around[2];
    int reorder;

    Debug("My_MPI_Init",0);

    // num of processes
    MPI_Comm_size(MPI_COMM_WORLD, &P);

    //calculate the number of processes per column and per row for the grid
    if(argc>2){
        P_grid[X_DIR] = atoi(argv[1]);
        P_grid[Y_DIR] = atoi(argv[2]);
        if(P_grid[X_DIR] * P_grid[Y_DIR] != P){
            Debug("ERROR Proces grid dimensions do not match with P ", 1);
        }
    }
    else{
        Debug("ERROR Wrong parameter input",1);
    }

    // Create process topology (2D grid)
    wrap_around[X_DIR] = 0;
    wrap_around[Y_DIR] = 0;
    reorder = 1; //reorder process ranks
```

```
136
137     // create grid_comm
138     int ret = MPI_Cart_create(MPI_COMM_WORLD, 2, P_grid, wrap_around, reorder, &grid_comm);
139     if (ret != MPI_SUCCESS){
140         Debug("ERROR: MPI_Cart_create failed",1);
141     }
142     //get new rank and cartesian coords of this proc
143     MPI_Comm_rank(grid_comm, &proc_rank);
144     MPI_Cart_coords(grid_comm, proc_rank, 2, proc_coord);
145     printf("(%i) (x,y)=(%i,%i)\n", proc_rank, proc_coord[X_DIR], proc_coord[Y_DIR]);
146     //calc neighbours
147     // MPI_Cart_shift(grid_comm, Y_DIR, 1, &proc_bottom, &proc_top);
148     MPI_Cart_shift(grid_comm, Y_DIR, 1, &proc_top, &proc_bottom);
149     MPI_Cart_shift(grid_comm, X_DIR, 1, &proc_left, &proc_right);
150     printf("(%i) top %i,  right  %i,  bottom  %i,  left  %i\n", proc_rank, proc_top,
    proc_right, proc_bottom, proc_left);
151 }
152
153 void Setup_Grid()
154 {
155     int x, y, s;
156     double source_x, source_y, source_val;
157     FILE *f;
158
159     Debug("Setup_Subgrid", 0);
160
161     if(proc_rank == 0){
162         f = fopen("input.dat", "r");
163         if (f == NULL){
164             Debug("Error opening input.dat", 1);
165         }
166         fscanf(f, "nx: %i\n", &gridsize[X_DIR]);
167         fscanf(f, "ny: %i\n", &gridsize[Y_DIR]);
168         fscanf(f, "precision goal: %lf\n", &precision_goal);
169         fscanf(f, "max iterations: %i\n", &max_iter);
170     }
171     MPI_Bcast(&gridsize, 2, MPI_INT, 0, grid_comm);
172     MPI_Bcast(&precision_goal, 1, MPI_DOUBLE, 0, grid_comm);
173     MPI_Bcast(&max_iter, 1, MPI_INT, 0, grid_comm);
174
175     /* Calculate dimensions of local subgrid */ //! We do that later now!
176     // dim[X_DIR] = gridsize[X_DIR] + 2;
177     // dim[Y_DIR] = gridsize[Y_DIR] + 2;
178
179     //! Step 7
180     int upper_offset[2] = {0,0};
181     // Calculate top left corner cordinates of local grid
182     offset[X_DIR] = gridsize[X_DIR] * proc_coord[X_DIR] / P_grid[X_DIR];
183     offset[Y_DIR] = gridsize[Y_DIR] * proc_coord[Y_DIR] / P_grid[Y_DIR];
184     upper_offset[X_DIR] = gridsize[X_DIR] * (proc_coord[X_DIR] + 1) / P_grid[X_DIR];
185     upper_offset[Y_DIR] = gridsize[Y_DIR] * (proc_coord[Y_DIR] + 1) / P_grid[Y_DIR];
186
187     // dimensions of local grid
188     dim[X_DIR] = upper_offset[X_DIR] - offset[X_DIR];
189     dim[Y_DIR] = upper_offset[Y_DIR] - offset[Y_DIR];
190     // Add space for rows/columns of neighboring grid
191     dim[X_DIR] += 2;
192     dim[Y_DIR] += 2;
193     //! Step 7 end
194
195     /* allocate memory */
196     if ((phi = malloc(dim[X_DIR] * sizeof(*phi))) == NULL){
197         Debug("Setup_Subgrid : malloc(phi) failed", 1);
198     }
199     if ((source = malloc(dim[X_DIR] * sizeof(*source))) == NULL){
200         Debug("Setup_Subgrid : malloc(source) failed", 1);
201     }
202     if ((phi[0] = malloc(dim[Y_DIR] * dim[X_DIR] * sizeof(**phi))) == NULL){
203         Debug("Setup_Subgrid : malloc(*phi) failed", 1);
204     }
205     if ((source[0] = malloc(dim[Y_DIR] * dim[X_DIR] * sizeof(**source))) == NULL){
206         Debug("Setup_Subgrid : malloc(*source) failed", 1);
207     }
```

```
208     for (x = 1; x < dim[X_DIR]; x++)
209     {
210         phi[x] = phi[0] + x * dim[Y_DIR];
211         source[x] = source[0] + x * dim[Y_DIR];
212     }
213 
214     /* set all values to '0' */
215     for (x = 0; x < dim[X_DIR]; x++){
216         for (y = 0; y < dim[Y_DIR]; y++)
217         {
218             phi[x][y] = 0.0;
219             source[x][y] = 0;
220         }
221     }
222     /* put sources in field */
223     do{
224         if (proc_rank==0)
225         {
226             s = fscanf(f, "source: %lf %lf %lf\n", &source_x, &source_y, &source_val);
227         }
228         MPI_Bcast(&s, 1, MPI_INT, 0, grid_comm);
229         if (s==3){
230             MPI_Bcast(&source_x, 1, MPI_DOUBLE, 0, grid_comm);
231             MPI_Bcast(&source_y, 1, MPI_DOUBLE, 0, grid_comm);
232             MPI_Bcast(&source_val, 1, MPI_DOUBLE, 0, grid_comm);
233             x = source_x * gridsize[X_DIR];
234             y = source_y * gridsize[Y_DIR];
235             x = x + 1 - offset[X_DIR]; // Step 7 --> local grid transform
236             y = y + 1 - offset[Y_DIR]; // Step 7 --> local grid transform
237             if(x > 0 && x < dim[X_DIR] -1 && y > 0 && y < dim[Y_DIR]-1){ // check if in local
    grid
238                 phi[x][y] = source_val;
239                 source[x][y] = 1;
240             }
241         }
242     }
243     while (s==3);
244 
245     if(proc_rank==0){
246         fclose(f);
247     }
248 }
249 
250 void Setup_MPI_Datatypes()
251 {
252     Debug("Setup_MPI_Datatypes",0);
253 
254     // vertical data exchange (Y_Dir)
255     MPI_Type_vector(dim[X_DIR] - 2, 1, dim[Y_DIR], MPI_DOUBLE, &border_type[Y_DIR]);
256     // horizontal data exchange (X_Dir)
257     MPI_Type_vector(dim[Y_DIR] - 2, 1, 1, MPI_DOUBLE, &border_type[X_DIR]);
258 
259     MPI_Type_commit(&border_type[Y_DIR]);
260     MPI_Type_commit(&border_type[X_DIR]);
261 }
262 
263 void Exchange_Borders()
264 {
265     Debug("Exchange_Borders",0);
266     // top direction
267     MPI_Sendrecv(&phi[1][1], 1, border_type[Y_DIR], proc_top, 0, &phi[1][dim[Y_DIR] - 1], 1,
    border_type[Y_DIR], proc_bottom, 0, grid_comm, &status);
268     // bottom direction
269     MPI_Sendrecv(&phi[1][dim[Y_DIR] - 2], 1, border_type[Y_DIR], proc_bottom, 0, &phi[1][0],
    1, border_type[Y_DIR], proc_top, 0, grid_comm, &status);
270     // left direction
271     MPI_Sendrecv(&phi[1][1], 1, border_type[X_DIR], proc_left, 0, &phi[dim[X_DIR]-1][1], 1,
    border_type[X_DIR], proc_right, 0, grid_comm, &status);
272     // right direction
273     MPI_Sendrecv(&phi[dim[X_DIR]-2][1], 1, border_type[X_DIR], proc_right, 0, &phi[0][1], 1,
    border_type[X_DIR], proc_left, 0, grid_comm, &status);
274 }
275 
```

```
276 double Do_Step(int parity)
277 {
278   int x, y;
279   double old_phi;
280   double max_err = 0.0;
281 
282   /* calculate interior of grid */
283     for (x = 1; x < dim[X_DIR] - 1; x++){
284         for (y = 1; y < dim[Y_DIR] - 1; y++){
285             if ((x + offset[X_DIR] + y + offset[Y_DIR]) % 2 == parity && source[x][y] != 1){
286                 old_phi = phi[x][y];
287                 phi[x][y] = (phi[x + 1][y] + phi[x - 1][y] + phi[x][y + 1] + phi[x][y - 1]) *
    0.25;
288                 if (max_err < fabs(old_phi - phi[x][y])){
289                     max_err = fabs(old_phi - phi[x][y]);
290                 }
291             }
292         }
293     }
294 
295   return max_err;
296 }
297 
298 void Solve()
299 {
300     int count = 0;
301     double delta;
302     double global_delta;
303     double delta1, delta2;
304 
305     Debug("Solve", 0);
306 
307     /* give global_delta a higher value then precision_goal */
308     global_delta = 2 * precision_goal;
309 
310     while (global_delta > precision_goal && count < max_iter)
311     {
312         Debug("Do_Step 0", 0);
313         delta1 = Do_Step(0);
314         Exchange_Borders();
315         Debug("Do_Step 1", 0);
316         delta2 = Do_Step(1);
317         Exchange_Borders();
318         delta = max(delta1, delta2);
319         MPI_Allreduce(&delta, &global_delta, 1, MPI_DOUBLE, MPI_MAX, grid_comm);
320         count++;
321     }
322 
323     printf("(%i) Number of iterations : %i\n", proc_rank, count);
324 }
325 
326 double* get_Global_Grid()
327 {
328     Debug("get_Global_Grid", 0);
329     //!! DEBUG only
330     for (size_t i = 0; i < dim[X_DIR]; i++)
331     {
332         for (size_t j = 0; j < dim[Y_DIR]; j++)
333         {
334             phi[i][j] = proc_rank;
335         }
336 
337     }
338 
339     // only process 0 needs to store all data!
340     double* global_phi = NULL;
341     if (proc_rank == 0) {
342         global_phi = malloc(gridsize[X_DIR] * gridsize[Y_DIR] * sizeof(double));
343         if (global_phi == NULL) {
344             Debug("get_Global_Grid : malloc(global_phi) failed", 1);
345         }
346     }
347 
```

```
348     // copy own part into buffer - flatten!
349     size_t buf_size = (dim[X_DIR] - 2) * (dim[Y_DIR] - 2) * sizeof(double);
350     double* local_phi = malloc(buf_size);
351     int idx = 0;
352     for (int x = 1; x < dim[X_DIR] - 1; x++) {
353         for (int y = 1; y < dim[Y_DIR] - 1; y++) {
354             local_phi[idx++] = phi[x][y];
355         }
356     }
357     printf("I'm proc %d and i have a buffer of size %zu\n", proc_rank, buf_size);
358 
359 
360     // only proc 0 needs sendcounts and displacements for the gatherv operation
361     int* sendcounts = NULL;
362     int* displs = NULL;
363     if (proc_rank == 0) {
364         sendcounts = malloc(P * sizeof(int));
365         displs = malloc(P * sizeof(int));
366 
367         // size and offset of different subgrids
368         //! Note that this only works if every process has the same subgrid
369         if (gridsize[X_DIR] % P_grid[X_DIR] != 0 || gridsize[Y_DIR] % P_grid[Y_DIR] != 0)
370         {
371             Debug("!!!A grid dimension is not a multiple of the P_grid in this direction!", 1)
    ;
372         }
373 
374         int subgrid_width = gridsize[X_DIR] / P_grid[X_DIR];
375         int subgrid_height = gridsize[Y_DIR] / P_grid[Y_DIR];
376         for (int px = 0; px < P_grid[X_DIR]; px++) {
377             for (int py = 0; py < P_grid[Y_DIR]; py++) {
378                 int rank = px * P_grid[Y_DIR] + py;
379                 sendcounts[rank] = subgrid_width * subgrid_height;
380                 displs[rank] = (px * subgrid_width * gridsize[Y_DIR]) + (py * subgrid_height);
381             }
382         }
383     }
384     Debug("get_Global_Grid : MPI_Gatherv", 0);
385     //! TODO this Gatherv does something wrong - all local grids are alright!!!
386     MPI_Gatherv(local_phi, (dim[X_DIR] - 2) * (dim[Y_DIR] - 2), MPI_DOUBLE, global_phi,
    sendcounts, displs, MPI_DOUBLE, 0, MPI_COMM_WORLD);
387 
388     free(local_phi);
389     if (proc_rank == 0) {
390         free(sendcounts);
391         free(displs);
392     }
393 
394     return global_phi;
395 }
396 
397 void Write_Grid_global(){
398     int x, y;
399     FILE *f;
400     char filename[40]; //seems danagerous to use a static buffer but let's go with the steps
401     sprintf(filename, "output_MPI_global_%i.dat", proc_rank);
402     if ((f = fopen(filename, "w")) == NULL){
403         Debug("Write_Grid : fopen failed", 1);
404     }
405 
406     Debug("Write_Grid", 0);
407 
408     for (x = 1; x < dim[X_DIR]-1; x++){
409         for (y = 1; y < dim[Y_DIR]-1; y++){
410             int x_glob = x + offset[X_DIR];
411             int y_glob = y + offset[Y_DIR];
412             fprintf(f, "%i %i %f\n", x_glob, y_glob, phi[x][y]);
413         }
414     }
415     fclose(f);
416 }
417 
418 void Write_Grid()
```

```
{
    double* global_phi = get_Global_Grid();
    if(proc_rank != 0){
        assert (global_phi == NULL);
        return;
    }
    int x, y;
    FILE *f;
    char filename[40]; //seems danagerous to use a static buffer but let's go with the steps
    sprintf(filename, "output_MPI%i.dat", proc_rank);
    if ((f = fopen(filename, "w")) == NULL){
        Debug("Write_Grid : fopen failed", 1);
    }

    Debug("Write_Grid", 0);

    for (x = 0; x < gridsize[X_DIR]; x++){
        for (y = 0; y < gridsize[Y_DIR]; y++){
            fprintf(f, "%i %i %f\n", x+1, y+1, global_phi[x*gridsize[Y_DIR] + y]);
        }
    }
    fclose(f);
    free(global_phi);
}

void Clean_Up()
{
    Debug("Clean_Up", 0);

    free(phi[0]);
    free(phi);
    free(source[0]);
    free(source);
}

int main(int argc, char **argv)
{
    MPI_Init(&argc, &argv);
    Setup_Proc_Grid(argc,argv); // was earlier MPI_Comm_rank(MPI_COMM_WORLD, &proc_rank);
    start_timer();

    Setup_Grid();
    Setup_MPI_Datatypes();

    Solve();

    // Write_Grid();
    Write_Grid_global();
    print_timer();

    Clean_Up();
    MPI_Finalize();
    return 0;
}
```