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:
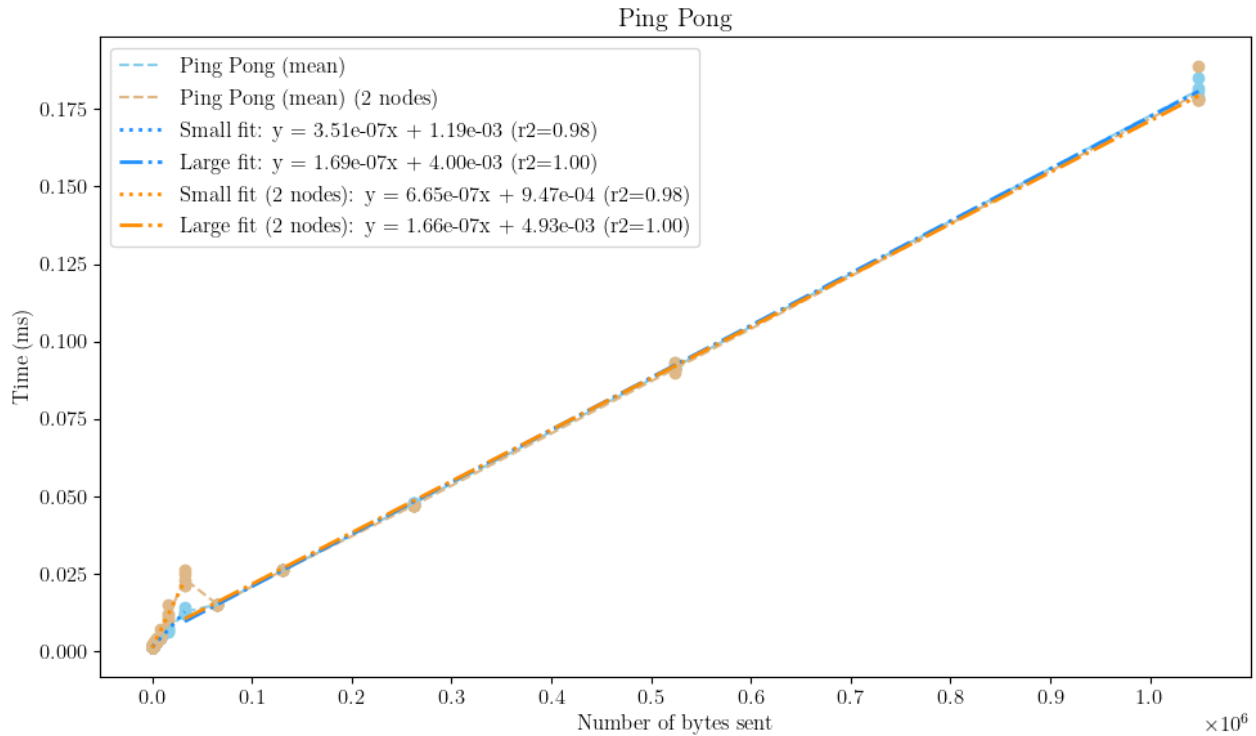
Figure 2: Ping Pong with MPI_SendRecv: Number of bytes sent vs. average time taken from 1000 pairs of send / receive. 5 runs shown for each size as scatter plot. Mean of these 5 runs shown as line. Blue small fit includes all data points up to 32768 bytes, blue large from there. Red small fit includes 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:
  $\texttt{total\_rows} - (\texttt{nr\_workers} - 1) \cdot floor(\frac{\texttt{total\_rows}}{\texttt{nr\_workers}})$.

- All other workers and the master (= rank 0) get the same number of rows: $floor(\frac{\texttt{total\_rows}}{\texttt{nr\_workers}})$.

- 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 $\times$ 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.

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.

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.

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:
TODO: **RUN ON DELFT BLUE!!!**

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

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

Note on different Versions:
For the following exercises the implementation will be slightly adapted to measure different performance aspects. To facilitate this, we will use defines to switch between different versions of the code at compile time. The final version of the poissonsolver can be found in the appendix for this section.

9

1.2.1 Over-relaxation (SOR)

We start of by rewriting the `Do_Step` routine to facilitate SOR updates. Furthermore, we need h^2, the grid spacing (which is 1 in our case) and the relaxation parameter ω to calculate the updated values. A quick test shows a speedup of roughly a factor of 10. More systematic tests will be done in the next section.

1.2.2 Optimal ω for 4 proc. on a 4x1 grid

With the power of a little python scripting we can easily test different values for ω and plot the results as seen in Figure 10.
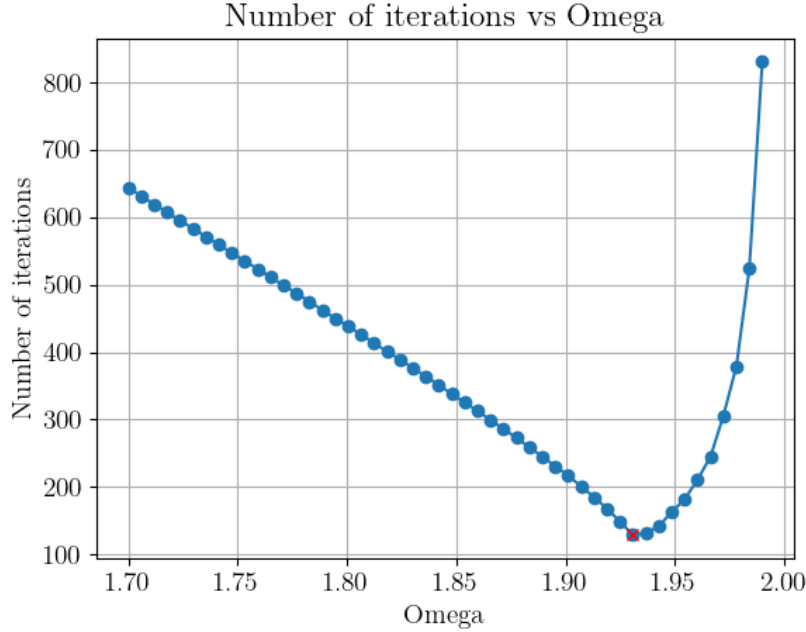
Figure 10: **Optimal ω for 4 processors on a 4x1 grid**

We find that the optimal ω is at about 1.93 for this setup with only 129 iterations. This constitutes a speedup of about 1825% compared to the sequential implementation.

N.B.: If not stated otherwise, we will use $\omega = 1.93$ for the following exercises.

1.2.3 Scaling behavior with larger grids

This investigation is carried out twice: Once with a 4×1 topology (as in the previous section) and once with a 2×2 topology. We use grid sizes of 10×10, 25×25, 50×50, 100×100, 200×200, 400×400, 800×800 and 1600×1600 and set $\omega = 1.95$ for all runs. The results are shown in Figure 11.
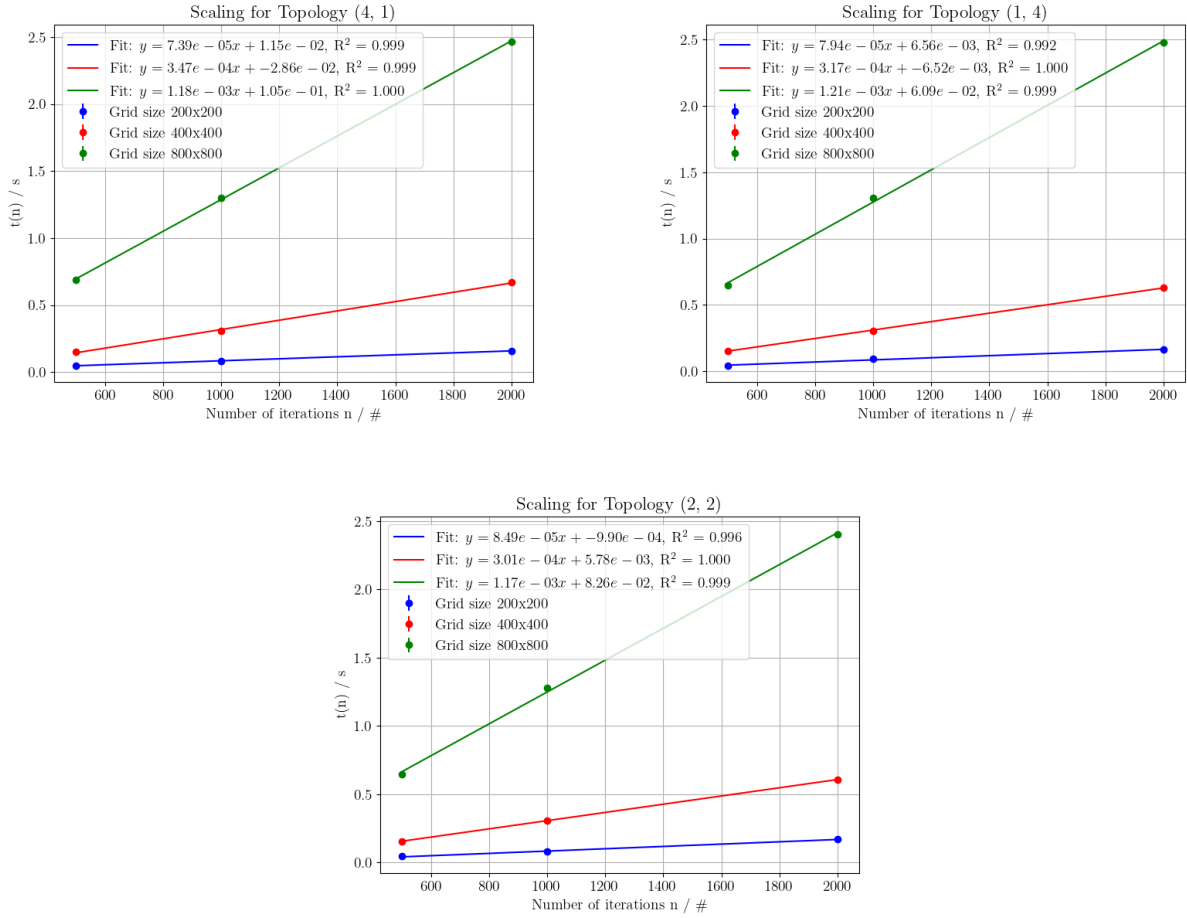
Figure 11: Scaling behavior of the Poisson solver with different grid sizes and processor topologies

As seen by the high R^2 values in the plots, the scaling behavior is very close to linear. We obtain the following scaling factors for the different grid sizes and topologies from the linear fits:

Topology	Gridsize	α	β
4×1	200×200	$7.39 \cdot 10^5$	$1.15 \cdot 10^2$
4×1	400×400	$3.47 \cdot 10^4$	$-2.86 \cdot 10^2$
4×1	800×800	$1.18 \cdot 10^3$	$1.05 \cdot 10^1$
1×4	200×200	$7.94 \cdot 10^5$	$6.56 \cdot 10^3$
1×4	400×400	$3.17 \cdot 10^4$	$-6.52 \cdot 10^3$
1×4	800×800	$1.21 \cdot 10^3$	$6.09 \cdot 10^2$
2×2	200×200	$8.49 \cdot 10^5$	$-9.90 \cdot 10^4$
2×2	400×400	$3.01 \cdot 10^4$	$5.78 \cdot 10^3$
2×2	800×800	$1.17 \cdot 10^3$	$8.26 \cdot 10^2$

Table 5: Scaling factors for different processor topologies for the Poisson solver
Using: $t(n) = \alpha + \beta \cdot n$ as a model

What can you conclude from the scaling behavior?
We see that the scaling behavior is very close to linear for both topologies. This means that the parallel implementation scales as expected with the number of grid points.
If we compare the scaling factors (β) for the two topologies we see that the 2×2 topology scales slightly better than the 4×1 and 1×4 topologies. This is not surprising, as the 2×2 topology has a more balanced communication workload balance. In the 2×2 topology every processor has two neighbors, while in the 4×1 and 1×4 topologies the processors at the ends only have one neighbor. This is a general trend: A topology which divides the grid into square / square-like parts will scale better than a topology which divides the grid

into long and thin parts.

In essence: We want to keep the communication between processors as balanced as possible to achieve the best scaling behavior. **Scaling of different grid sizes:**

We see that larger grids take longer for the same amount of iterations. This is also to be expected, as the number of grid points grows quadratically with the grid size. a 400×400 grid has 4 times as many grid points as a 200×200 grid and therefore takes roughly 4 times as long to calculate.

1.2.4 Scaling behavior [**Theory - no measurements**]

If I could choose between a 16×1, 8×2, 4×4, 2×8, 1×16 topology, I would choose the 4×4 topology. This is because the 4×4 topology has the most balanced communication workload balance, as detailed in the **Shining** in subsubsection 1.2.3.

1.2.5 Iterations needed for convergence scaling

We investigate the number of iterations needed for convergence using the 4×1 topology square grids with sidelength: $10, 25, 50, 100, 200, 400, 800, 1600$. The results for different ω are shown in Figure 12.
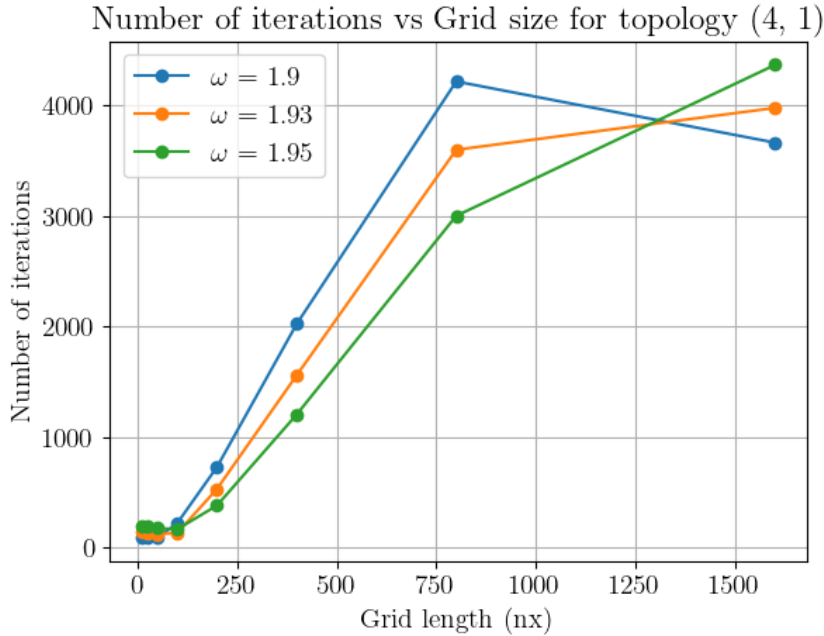
Figure 12: Iterations needed for convergence with different grid side lengths

We can clearly see that the number of iterations till convergence increases with the problem size. At first, I expected linear growth proportional to the number of gridpoints. However, it turns out that the number of iterations actually grow slower and in a square root like fashion. This can be seen by the linear behavior in the plot of grid-side length against iterations.

Why is the number of iterations needed for convergence $\propto \sqrt{g}$?

Our poisson problem is a discretized system in 2D space. The condition number of the matrix we have to solve is proportional to the number of gridpoints in our system. SOR uses the spectral properties of the matrix to solve in a way such that the dominant error mode takes time proportional to the diameter of the domain to converge. This means it is proportional to $\sqrt{g} = \sqrt{n_x \cdot n_y}$.

Why does omega with the best performance change with the grid size?

As can be seen in Figure 12 $\omega = 1.9$ beats the other two values for very small and the largest gridsize. For different gridsizes we get differnetly sized matrices we have to solve. SOR overrelaxes high-frequency errors and underrelaxes low-frequency errors (the later for stability). The optimal ω is therefore dependent on the gridsize and the error modes present in the system. In our current example, it might be that $\omega = 1.9$ is a good compromise for the grid sizes we are looking at.

1.2.6 Error as a function of the iteration number

With the same 4×1 topology and grid sizes of 800×800 the error for 15000 iterations is tracked using $\omega = 1.93$. The results are shown in Figure 13.
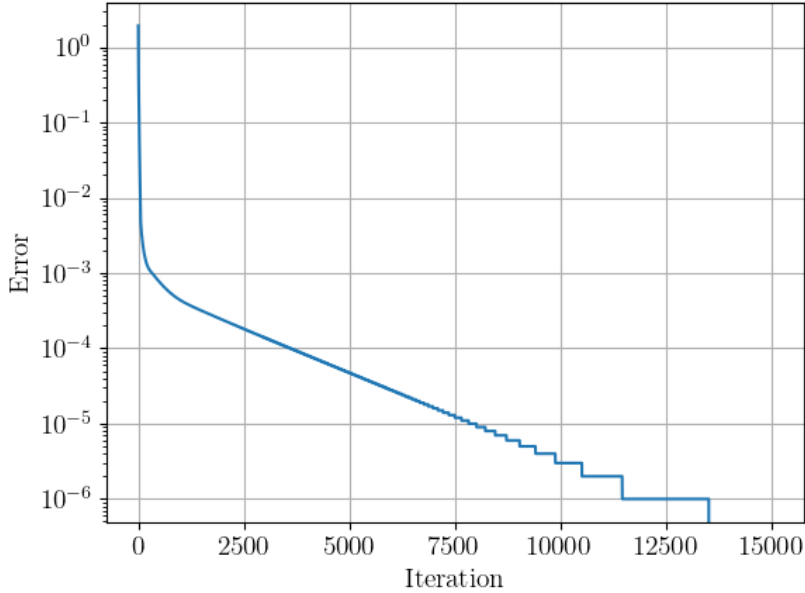
Figure 13: Error as a function of the iteration number

At first the error decreases rapidly in the first few iterations to about 10^{-3} (logarithmic scale!). After that the error decreases more slowly until it is below floating point precision. **Note:** All calculations are done using double precision floating point numbers and only the error recording was done using single precision which leaves the step-like artifacts in the plot.

1.2.7 Optional - Gain performance by reducing `MPI_Allreduce` calls

The last subsection showed us that the error reduces monotonically. We might be able to save some time by leaving out some checks and maybe check the global error every 10th or 100th iteration only.

First, we should benchmark if it is at all wise to optimize here, by measuring how long the `MPI_Allreduce` call takes. We can do this by measuring the time needed for the `MPI_Allreduce` call in the `Do_Step` function and summing up to get the total time spent in `MPI_Allreduce` calls.

We again solve with a 4×1 topology, $\omega = 1.93$ and a 800×800 grid: It takes roughly 20 seconds of which the processors spend around 1 - 2 seconds in the `MPI_Allreduce` call. This is a significant amount of time $((7.0 \pm 0.4)\%)$. This means we would save some time by reducing the number of `MPI_Allreduce` calls and calculating 9 (0.25% of total) more iterations wouldn't hurt us too bad because it takes 3601 to converge!

We run the program three times with `MPI_Allreduce` calls every 1, 10 and 100 iterations and get the speedups in `MPI_Allreduce` calls as shown in Table 6.

Iterations	`MPI_Allreduce` - speedup (factor)	calculated overall speedup (%)
1	1.00	0
10	6.0 ± 2.0	5.9 ± 0.5
100	62 ± 6	6.9 ± 0.4

Table 6: Speedup in `MPI_Allreduce` calls for different iteration counts and calculated overall speedup (%)

As can be clearly seen from the table we can gain around 6 % using `MPI_Allreduce` calls every 10 iterations and around 7 % using `MPI_Allreduce` calls every 100 iterations. This is a significant speedup for a very small change in the code.

Note: The speedup is calculated to account for fluctuations in the runtime of the program, due to other processes running on the same machine / cluster.

1.2.8 Reduce border communication

Another way to reduce communication overhead is to reduce the number of border exchanges. To investigate if this yields a speedup we run the program on a 4×1 topology, $\omega = 1.93$ and different grid sizes and track the iterations and time as seen in Figure 14.
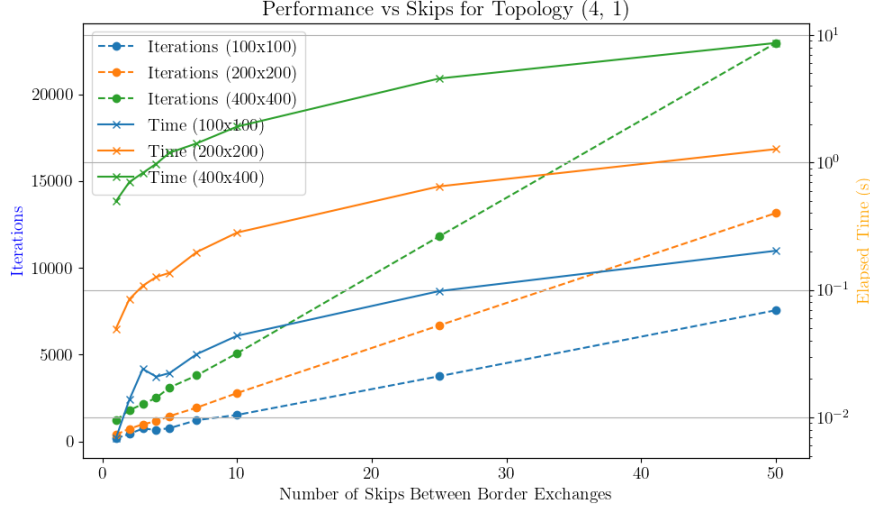
Figure 14: Speedup by reducing border exchanges

Running the with different numbers of skipped border exchanges naturally slows down convergence, meaning we need more iterations to reach the same error. For all tested grid sizes the initial SOR version without skipping border exchanges has the fewest iterations needed to convergence and also the fastes runtime.

What can you conclude from the results?
We can conclude that reducing the number of border exchanges does not yield a speedup. The reason for this is that we have to calculate more iterations to converge to the solution which outweighs the gains from reduced communication overhead. Interestingly, for the 100×100 grid there exists a local minimum in time at 4 skipped border exchanges compared to 3 skipped. This is likely due to our source field distribution and thus specific to our problem.

1.2.9 Optimize `Do_Step` loop

In `Do_Step` we iterate over the whole grid but only update one of the two parities at a time. This means we can split the loop into two loops, one for each parity. We start out with something like this:

```
for (x = 1; x < dim[X_DIR] - 1; x++){
    for (y = 1; y < dim[Y_DIR] - 1; y++){
        if ((x + offset[X_DIR] + y + offset[Y_DIR]) % 2 == parity && source[x][y] != 1){
            ...
```

and we change it to:

```
int start_y;
for (x = 1; x < dim[X_DIR] - 1; x++){
    start_y = ((1 + x + offset[X_DIR] + offset[Y_DIR]) % 2 == parity) ? 1 : 2;
    for (y = start_y; y < dim[Y_DIR] - 1; y += 2){
        if (source[x][y] != 1){
            ...
```

The basic idea is to avoid y-coordinates which are not in the parity we are currently updating. We measure 10 runs for a 800×800 grid and a 4×1 topology with $\omega = 1.93$ and get the following times:

$$t_{\text{no\_improvements}} = (5.59 \pm 0.05)\,\text{s} \qquad \text{and} \qquad t_{\text{loop\_improvements}} = (4.64 \pm 0.07)\,\text{s}$$

So we get a minimal speedup of about 17% by optimizing the loop which is a enormous speedup for such a small change.

Why does this make such a difference
The reason for this is that we avoid unnecessary looping and if statements. This means that we have less overhead in the loop and can therefore calculate faster by skipping the unnecessary loop entries.

1.2.10   Optional - Time spent within `Exchange_Borders`

We can measure the time spent in `Exchange_Borders` by adding a timer to the function. We run the program with $\omega = 1.93$ and different topologies and grid sizes and get the results shown in Figure 15.
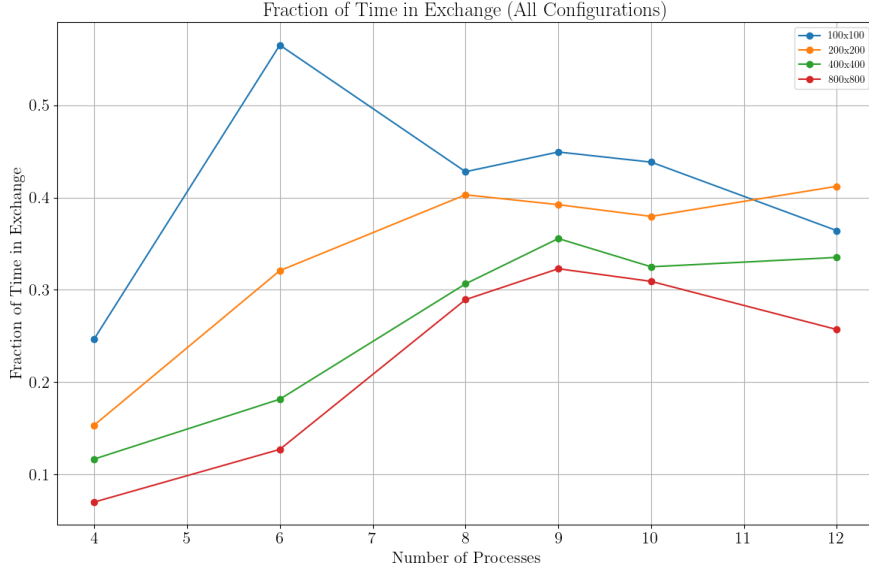
Figure 15: Fraction of total time spent in `Exchange_Borders`

As we can clearly see, the time spent in `Exchange_Borders` is initially smaller and grows with processor count. The curves are generally shifted downward for larger gridssizes.

Interpretation:
One would expect larger grid sizes to be more computationally expensive and we have already established that iterations take longer the bigger the grid. Communication obviously also takes longer for a larger grid because we have more data to sent. However, the circumference of a square grows linearly, while the area grows quadratically. The quadratic growth of the area is the reason for the downward shift in the curves for larger grid sizes because the communication overhead grows slower than the computational overhead for larger grids.

When is the time spent in `Exchange_Borders` significant / comparable to computation?
As can be seen in Figure 15 the time spent in `Exchange_Borders` is significant for all grid sizes from the start (between 5 and 25%). Thereafter it grows to around 30% to 45% for 9 processors. This means that the time spent in `Exchange_Borders` is significant for all grid sizes and processor counts, but especially as the processor count grows.

1.2.11   Latency and bandwith in `Exchange_Borders`

We use the configurations from subsubsection 1.2.3: 4×1, 2×2 and 3×3 topologies with grid sizes of 200×200, 400×400 and 800×800 and $\omega = 1.95$. We obtain the results in Table 7.

Table 7: Metrics for `Exchange_Borders` latency and bandwith

Topology	Grid Size	Latency (ms)	Latency (%)	Bandwidth ($\mathrm{B\,s^{-1}}$)	Total Data (B)
4x1	200x200	370 ± 44	6.6	447 314 206	135 548 032
4x1	400x400	328 ± 39	6.0	511 267 773	135 548 032
4x1	800x800	401 ± 38	7.1	390 446 955	135 548 032
2x2	200x200	346 ± 83	6.2	426 689 734	108 546 432
2x2	400x400	281 ± 74	5.2	576 865 986	108 546 432
2x2	800x800	288 ± 71	5.3	558 562 482	108 546 432
3x3	200x200	1054 ± 204	25.2	78 386 044	72 364 288
3x3	400x400	1147 ± 229	27.6	81 623 075	72 364 288
3x3	800x800	1082 ± 148	26.7	60 819 112	72 499 296

Interpretation:

As can be seen the latency is more or less comparable between the 4×1 and 2×2 topologies. The 3×3 topology has a significantly higher latency. This is due to the fact that the 3×3 topology has more neighbors to communicate with.

1.2.12 Exchange Border potential improvements

Indeed we communicate twice as much as we need after each `Do_Step` call. We shall analyze this considering the following points:

- address of the first point to exchange: This depends on the parity of the processor. It is simply the first or second point in the grid depending on the parity (leaving out the edge case where the processor only has one data-point).

- the number of points to exchange: This normally is the number of points in the grid minus ghost cells divided by two. However, this may change if there is an odd number of points in the grid (then we have to exchange one more or one less point).

- the number of points in between grid points that have to be exchanged: The stride of the data will change. Currently we exchange every point for one direction and every `dim[Y_DIR]`-th point for the other direction. This can be optimized to exchange every second point in one direction and every second `dim[Y_DIR]`-th point in the other direction.

Is it worth it?

For smaller gridsizes it is not worth it to optimize the border exchange. The time spent in the border exchange might be significant in relative terms, but the absolute time is still small. For larger gridsizes it might be worth it to optimize the border exchange. As we have seen, this becomes more significant as the processor count and gridsizes grow. For our current problem and similarly sized problems the effort put into optimizing the border exchange is certainly not worth it.

2 Finite elements simulation

We will now shift our focus to a more general grid which is based on triangulation. In this section we will compare our parallel implementation from the previous section and disect the differences and similarities. For that reason we shall use the same sources in our grid as given in `sources.dat`.

Note that the sections for the exercises will be labeled as (2.1, 2.2, 2.3, ...) corresponding to exercises (4.1, 4.2, 4.3, ...) in the lab manual.

2.1 Code understanding & `Exchange_Borders`

The first step is to read through the code in **MPI_Fempois.c** and to understand it. Furthermore, we have to implement the `Exchange_Borders` function for which only a skeleton is given. The function should exchange the border values of the local grid with the neighboring processes.

The implementation of this function is quite straight forward. We only have to loop over all the neighbors of a process and send out the border values and receive the border values from the neighbors. The function is implemented as follows:

```
void Exchange_Borders(double *vect)
{
    for (size_t i = 0; i < N_neighb; ++i)
    {
        MPI_Sendrecv(vect, 1, send_type[i], proc_neighb[i], 0, //send
                     vect, 1, recv_type[i], proc_neighb[i], 0, //recv
                     grid_comm, &status);
    }
}
```

2.2 Time benchmarking

Next we turn our attention to timing of different sections in the code.

We have to measure:

- Time spent in computation

- Time spent exchanging information with neighbors

- Time spent doing global communication

- Idle time

We setup the following variable to measure / deduce the time spent in the different sections:

```
    double total_time = 0.0;
    double exchange_time_neighbors = 0.0;
    double exchange_time_global = 0.0;
    double compute_time = 0.0;
```

We will measure the time spent in computations by timing the solve function and subtracting the time spent in the `MPI_Allreduce` calls. The time spent in the `MPI_Allreduce` calls is the time spent in global communication. The time spent in exchanging information with neighbors is the time spent in the `Exchange_Borders` function. Finally, the idle time can be determined by summing up the differences between the cores total time and the slowest cores total time. Note that this way of calculating the idle time is an approximation since it is assumed that the slowest core doesn't have any idle time. However, I've discussed this with the TA and he said that this is a valid way of calculating the idle time for this exercise.

The commandline output for runs is as shown in Figure 16 for an example run:

```
(2) - Exchange time (neighbors): 0.007183
(2) - Exchange time (global): 0.002372
(2) - Sum of times (compute + exchange (global & local)): 0.062241
(2) - Total time: 0.069645
(0) - Total time: 0.069800
(1) - Compute time: 0.051027
(1) - Exchange time (neighbors): 0.005517
(1) - Exchange time (global): 0.004273
(1) - Sum of times (compute + exchange (global & local)): 0.060816
(1) - Total time: 0.069416
(3) - Compute time: 0.051977
(3) - Exchange time (neighbors): 0.006824
(3) - Exchange time (global): 0.003341
(3) - Sum of times (compute + exchange (global & local)): 0.062142
(3) - Total time: 0.069399
```

Figure 16: Timing for the different sections.
(x) . . . denotes the process rank
Compute time . . . time spent in the `solve` function only on computing
Exchange time (neighbors) . . . time spent in `Exchange_Borders`
Exchange time (neighbors) . . . time spent in `MPI_Allreduce` calls
Sum of times . . . total time spent in compute and communication (excluding setup / idle time)
Total time . . . total time spent in the program

The idle time is calculated as denoted above and therefore not shown in the output in Figure 16. We get the following results in Table 8:

Top.	Grid Size	Total (avg)	Comp. (avg)	Ex. Neighb. (avg)	Ex. Global (avg)	Idle (avg)
1x4	100x100	12.5	1.1	3.9	0.7	
1x4	200x200	85.1	1.6	12.7	0.0	
1x4	400x400	1192.5	7.2	118.3	1.3	
2x2	100x100	11.6	0.9	1.8	2.9	
2x2	200x200	85.0	2.9	11.2	0.6	
2x2	400x400	1173.7	8.9	110.0	0.9	

Table 8: Rank averaged time benchmark for different grid sizes and topologies.
All times are in milliseconds.

We see that the total time is comparable between the two topologies for all grid sizes. Furthermore, the total runtime also increases non-surprisingly with the gridsize.
Why does it increase faster than linearly?
One could expect, that the grid with 200×200 elements would take 4 times as long as the grid with 100×100 elements. However, the runtime is 6.8 times longer. This happens because additionally to the higher number of grid points the algorithm also takes longer (more iterations) to converge.
Analysis of the different times
To get a better grasp on the data a stacked bar plot, as shown in Figure 17, is created. We immediately see that the bulk of the time is spent on computing the solution. The second biggest contributor is the global exchange time, followed by local exchange time and idle time (except for 2×2 on the 100×100 grid).
That computation takes up the biggest part of the time is of non surprise especially on the bigger grids this is to be expected. Rather surprisingly the global excahnge time comes in second. This begs the question why two lines of the form:

```
1  MPI_Allreduce(... , ... , 1, MPI_DOUBLE, MPI_SUM, grid_comm);
```

take up this much time. This actually comes down to masked idle time. While the operation itself only sums up the values of 4 double, the operation is blocking and therefore the other cores have to wait for the slowest core to finish. If we look back at the definition of idle time, we defined it as the difference of the total time of the slowest core and the total time of the current core. However, as stated above, this does not take waiting time in MPI calls (like `MPI_Allreduce`) into account. Certainly, this explains now that the global exchange time is high, because every core has to wait for the others to synchronize to compute the `MPI_Allreduce`.
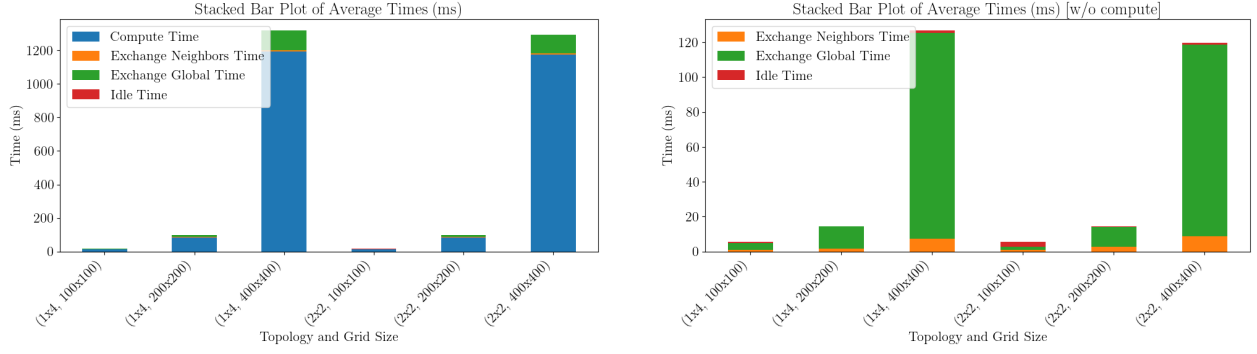
Figure 17: Scaling behavior of the Poisson solver with different grid sizes and processor topologies

2.3 Data exchange amount

This section is about the amount of data exchanged each iteration among one process with all its neighbors. We assume a uniformly triangulated grid which is partitioned stripe-wise and distribution over P processes. Furthermore, we assume that each process has to send the same amount of data. Indeed, this is not generally the case but for examples with periodic boundary conditions this is for example a valid assumption.

Now we see that every process has to communicate with $2d$ neighbors, where d is the dimension of the grid, under our assumptions there are 2 neighboring processes. With the assumption of a n^2 grid, our process communicates n values with each of these neighbors. For striped partitioning we get:

$$\text{Data exchanged per Process} = 2n$$

or in total:

$$\text{Data exchanged} = 2n \cdot P$$

Let's check for the extreme case 1000×1000 grid and $P = 500$ processes. We get:

$$\text{Data exchanged} = 2 \cdot 1000 \cdot 500 = 1000000$$

Which is the same amount of data as there are datapoints. This makes sense because every process has to communicate the top row upwards and the bottom row downwards.

Note, that we could even do worse if we assigned every process a single row. In this case every process would have to communicate the same data upward and downward. This would result in a data exchange of $2 \cdot 1000 \cdot 1000 = 2000000$ which is double the amount of data as there are datapoints.

For a box partitioning a process has to communicate $n/\sqrt{P}$ (assuming divisibility with all neighbors) with each of its 4 neighbors. We get:

$$\text{Data exchanged per Process} = 4 \cdot n/\sqrt{P}$$

or in total:

$$\text{Data exchanged} = 4 \cdot n \cdot \sqrt{P}$$

This means that a striped partitioning is less efficient compared to a boxed partitioning starting from $P = 4$, as can be seen in Figure 18.
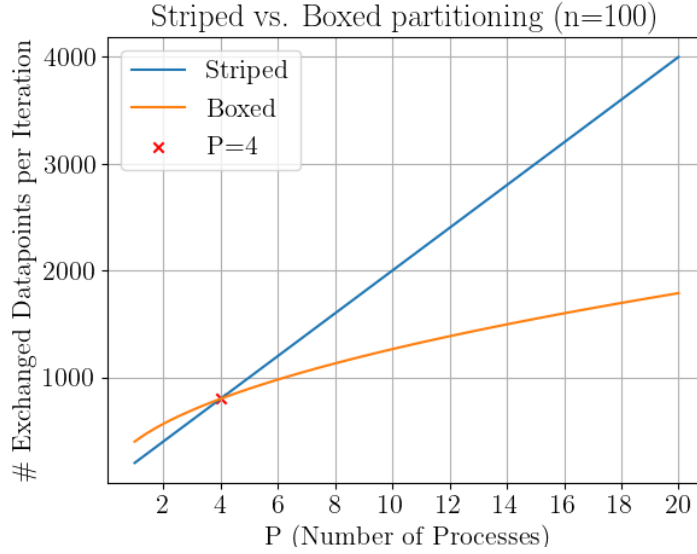
Figure 18: Striped vs. Boxed partitioning on a 100×100 grid using P processors.

2.4 Unbalanced communication

In the last section we assumed that every process has to communicate with the same amount of neighbors in our given scenario. That is actually not entierly true. There is an imbalance, even if just a small one.
But where does this imbalance come from?
Let's take a look at a **uniformly triangulated grid** with $P = 4$ processes. We assume that the grid is box-partitioned as given in Figure 19.
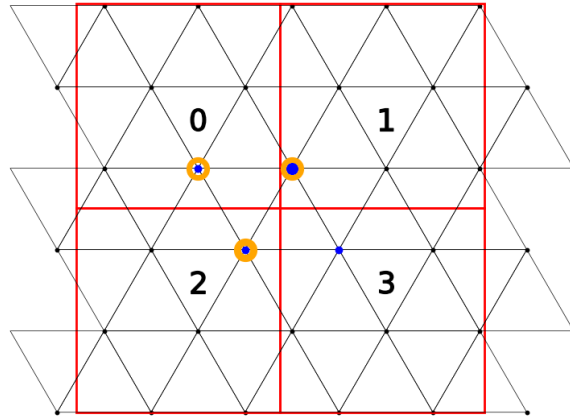
Figure 19: Box partitioning of a uniformly triangulated grid with $P = 4$ processes.
One point (big-blue) in 1 (and similarly in 3) has to communicate its value to 3 neighbors (small-blue).
Another point (big-orange circle) in 2 (and similarly in 4) has to communicate its value to 2 neighbors (small-orange circles).

We see that the geometry of a given uniform triangulated grid leads to an imbalance in communication. This imbalance is usually not a big problem, especially for bigger grids with comparably small amounts of processors

because only 2 points have to communicate with 3 neighbors. However, for smaller grids or proportionally high processor counts the imbalance is more significant.

Looking at a 3×3 grid with $P = 9$ processors, we see that the imbalance is more significant as shown in Figure 20.
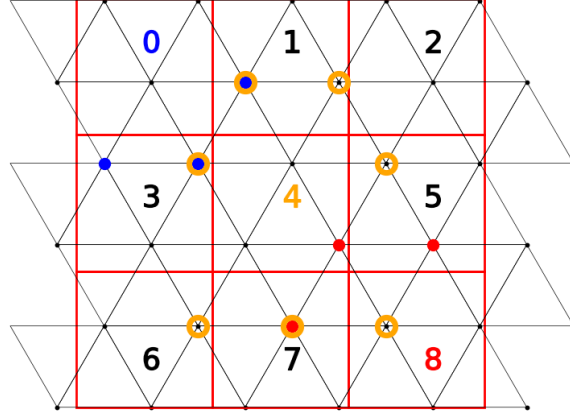
Figure 20: Box partitioning of a uniformly triangulated grid with $P = 9$ processes.
Corner (0/8 - blue/red) processes have to communicate their values to 2 or 3 neighbors respectively (1 and 3 - blue or 4, 5 and 7 - red).
Central (4 - orange) processes have to communicate their value to 6 neighbors (1, 3, 5, 6, 7 and 8).

As we can see the imbalance comes from the partitioning geometry on the uniform triangulated grid. Because our processor grid is rectangular the results will always, in one way or another come out as shown in the schematic above.
For 3×3 grid we have 4 corner processes which have to communicate with 2 or 3 neighbors and 1 central process which has to communicate with 6 neighbors. This is a significant imbalance and compared to the 2×2 grid it is not negligible, because the central process has to communicate more than 2 extra points (whole edges of datapoints) to its neighbors.

2.5   Estimations: communication time $\equiv$ computation time

2.6   4.6

TODO: **Run shell-script on DB**

3 Eigenvalue solution by Power Method on GPU

Appendix - Introductory exercise

The following code was used for the ping pong task:

```c
#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);
```

```
69            MPI_Get_count(&status, MPI_INT, &number_of_elements_received);
70
71            for (i=0; i<SAMPLE_COUNT; i++)
72            {
73                MPI_Recv(myArray, number_of_elements_received, MPI_INT, 0, 0,
74                MPI_COMM_WORLD, MPI_STATUS_IGNORE);
75                MPI_Send(myArray, number_of_elements_to_send, MPI_INT, 0, 0,
76                MPI_COMM_WORLD);
77            } // end of for-loop
78        }
79    }
80
81    // Finalize MPI
82    MPI_Finalize();
83
84    return 0;
85 }
```

For the bonus task, the following code was used:

```
1  #include <stdio.h>
2  #include <stdlib.h>
3  #include <mpi.h>
4
5  // Maximum array size 2^20= 1048576 elements
6  #define MAX_EXPONENT 20
7  #define MAX_ARRAY_SIZE (1<<MAX_EXPONENT)
8  #define SAMPLE_COUNT 1000
9
10 int main(int argc, char **argv)
11 {
12    // Variables for the process rank and number of processes
13    int myRank, numProcs, i;
14    MPI_Status status;
15
16    // Initialize MPI, find out MPI communicator size and process rank
17    MPI_Init(&argc, &argv);
18    MPI_Comm_size(MPI_COMM_WORLD, &numProcs);
19    MPI_Comm_rank(MPI_COMM_WORLD, &myRank);
20
21
22    int *myArray = (int *)malloc(sizeof(int)*MAX_ARRAY_SIZE);
23    if (myArray == NULL)
24    {
25        printf("Not enough memory\n");
26        exit(1);
27    }
28    // Initialize myArray
29    for (i=0; i<MAX_ARRAY_SIZE; i++)
30        myArray[i]=1;
31
32    int number_of_elements_to_send;
33    int number_of_elements_received;
34
35    // PART C
36    if (numProcs < 2)
37    {
38        printf("Error: Run the program with at least 2 MPI tasks!\n");
39        MPI_Abort(MPI_COMM_WORLD, 1);
40    }
41    double startTime, endTime;
42
43    // TODO: Use a loop to vary the message size
44    for (size_t j = 0; j <= MAX_EXPONENT; j++)
45    {
46        number_of_elements_to_send = 1<<j;
47        if (myRank == 0)
48        {
49            myArray[0]=myArray[1]+1; // activate in cache (avoids possible delay when sending
    the 1st element)
50            startTime = MPI_Wtime();
51            for (i=0; i<SAMPLE_COUNT; i++)
52            {
53                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  }
```

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

char* getbuffer(MM_input *in, size_t size_of_buffer){
    char* buffer = (char*)malloc(size_of_buffer * sizeof(char));
    if (buffer == 0)
    {
        printf("Buffer couldn't be allocated.");
        return NULL;
    }
    size_t offset = 0;
    memcpy(buffer + offset, &in->rows, sizeof(size_t));
    offset += sizeof(size_t);
    size_t matrix_size = in->rows * NCA * sizeof(double);
    memcpy(buffer + offset, in->a, matrix_size);
    offset += matrix_size;
    memcpy(buffer + offset, in->b, NCA*NCB*sizeof(double));
    return buffer;
}

MM_input* readbuffer(char* buffer, size_t size_of_buffer){
    MM_input *mm = (MM_input*)malloc(sizeof(MM_input));

    mm->rows = ((size_t*)buffer)[0];
    size_t offset = sizeof(size_t);
    size_t matrix_size =  mm->rows * NCA;
    mm->a = (double*)malloc(sizeof(double)*matrix_size);
    mm->b = (double*)malloc(sizeof(double)*matrix_size);
    memcpy(mm->a, &(buffer[offset]), matrix_size);
    offset += matrix_size;
    memcpy(mm->b, &(buffer[offset]), NCA*NCB*sizeof(double));
    free(buffer);
    return mm;
}


void setupMatrices(double (*a)[NCA], double (*b)[NCB], double (*c)[NCB]){
    for (size_t i = 0; i < NRA; i++) {
        for (size_t j = 0; j < NCA; j++) {
            a[i][j] = i + j;
        }
    }

    for (size_t i = 0; i < NCA; i++) {
        for (size_t j = 0; j < NCB; j++) {
            b[i][j] = i * j;
        }
    }

    for (size_t i = 0; i < NRA; i++) {
        for (size_t j = 0; j < NCB; j++) {
            c[i][j] = 0;
        }
    }
}

double multsum(double* a,double* b_transposed, size_t size){
    double acc = 0;
    for (size_t i = 0; i < size; i++)
    {
        acc += a[i]*b_transposed[i];
    }
    return acc;
}

double productSequential(double *res) {
    // dynamically allocate to not run into stack overflow - usually stacks are
    // 8192 bytes big -> 1024 doubles but we have 1 Mio. per matrix
    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!
194     size_t i;
195     for (i = 0; i < (num_workers-1); ++i)
196     {
197         MM_input *data = (MM_input*)malloc(sizeof(MM_input));
198         data->rows = rows_per_worker;
199         data->a = (double*)(a + (row_end_first + rows_per_worker*i));
200         data->b = (double*)(b_transposed); // send everyting - all needed
201         buffer = getbuffer(data, total_size);
202         printf("nr_worker - %zu\n", i);
203         MPI_Isend(buffer, total_size, MPI_CHAR, i+2, i+1,MPI_COMM_WORLD, &requests[i+1]);
204         free(data);
205     }
206     double* my_a = (double*)(a + (row_end_first + rows_per_worker*i));
207
208     //I multiply the rest
209     size_t offset = 0;
210     for (size_t row = (NRA-rows_per_worker); row < NRA; row++)
211     {
212         for (size_t col = 0; col < NCB; col++)
213         {
214             res[row * NCB + col] = multsum(my_a+offset, (((double*)b_transposed)+col*NCA), NCA
    );
215         }
216         offset += NCA;
217     }
218     printf("My c: \n");
219     //wait for rest
220     MPI_Status stats[num_workers];
221     if(MPI_Waitall(num_workers, requests, stats) == MPI_ERR_IN_STATUS){
222         printf("Communication failed!!! - abort\n");
223     }
224     printf(">>>Everything sent and recieved\n");
225
226     // reviece rest
227     size_t buf_size = sizeof(double)*row_end_first*NCB;
228     double* revbuf;
229     offset = 0;
230     for (size_t worker = 0; worker < num_workers; worker++)
231     {
232         revbuf = (double*)malloc(buf_size); //first gets largest buffer
233         MPI_Recv(revbuf, buf_size/sizeof(double), MPI_DOUBLE, worker+1, worker, MPI_COMM_WORLD
    ,&stats[worker]);
234         memcpy(&res[offset/sizeof(double)], revbuf, buf_size);
235         free(revbuf);
236         offset += buf_size;
237         buf_size = sizeof(double)*rows_per_worker*NCB;
238     }
239     double time = MPI_Wtime()-start_time;
240     //free all pointers!
241     free(a);
242     free(b);
243     free(b_transposed);
244     free(c);
245     return time;
246 }
247
248
249
250 double work(int rank, size_t num_workers){
251     size_t rows_per_worker = NRA / (num_workers+1);
252     char* buffer;
253     MPI_Status status;
254     if (rank == 1) // first always get's most work
255     {
256         rows_per_worker = NRA - rows_per_worker*num_workers;
257     }
258     size_t size_of_meta = sizeof(size_t);
259     size_t size_of_a = sizeof(double)*rows_per_worker*NCA;
260     size_t buffersize = size_of_meta+size_of_a + SIZE_OF_B;
261     buffer = (char*)malloc(buffersize);
262
263     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
```

```
336    MPI_Finalize();
337    return 0;
338 }
```

Appendix - Poisson solver

The parallel Poisson solver used the following code:

```
1  /*
2   * MPI_Poisson.c
3   * 2D Poison equation solver (parallel version)
4   */
5
6  #include <stdio.h>
7  #include <stdlib.h>
8  #include <math.h>
9  #include <time.h>
10 #include <mpi.h>
11 #include <assert.h>
12
13 #define DEBUG 0
14
15 #define max(a,b) ((a)>(b)?a:b)
16
17
18 // defines for Exercises!
19
20 #define SOR 1
21 #define MONITOR_ERROR 1
22 #define FAST_DO_STEP_LOOP
23 // #define MONITOR_ALLREDUCE 1
24 // #define ALLREDUCE_COUNT 100
25 #define MONITOR_EXCHANGE_BORDERS
26 #define SKIP_EXCHANGE
27
28 #define DEFINES_ON (SOR || MONITOR_ERROR || 0)
29 //defines end
30
31 enum
32 {
33     X_DIR, Y_DIR
34 };
35
36 // only needed for certain configs!
37 #ifdef SOR
38 double sor_omega = 1.9;
39 #endif
40 #ifdef MONITOR_ERROR
41 double *errors=NULL;
42 #endif
43 #ifdef MONITOR_ALLREDUCE
44 double all_reduce_time = 0;
45 #endif
46 #ifdef MONITOR_EXCHANGE_BORDERS
47 double total_exchange_time = 0.0;   // Total time spent in exchanges
48 double total_latency = 0.0;         // Total latency
49 double total_data_transferred = 0.0; // Total data transferred
50 int num_exchanges = 0;              // Number of exchanges
51 #endif
52 #ifdef SKIP_EXCHANGE
53 size_t skip_exchange;
54 #endif
55
56 /* global variables */
57 int gridsize[2];
58 double precision_goal;    /* precision_goal of solution */
59 int max_iter;      /* maximum number of iterations alowed */
60 int P; //total number of processes
61 int P_grid[2]; // process grid dimensions
62 MPI_Comm grid_comm; //grid communicator
63 MPI_Status status;
64 double hx, hy;
```

```c
/* 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);
    }
}
```

```c
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);
        }
        #ifdef SOR
        if (argc>3)
        {
            // get sor from args
            sor_omega = atof(argv[3]);
            printf("Set sor_omega over argv to %1.4f\n", sor_omega);
        }
        #endif
        #ifdef SKIP_EXCHANGE
        if (argc > 4)
        {
            skip_exchange = atoi(argv[4]);
            printf("Set skip_exchange over argv to %zu\n", skip_exchange);
        }
        else{
            skip_exchange = 1;
            printf("Set skip_exchange to default value 1\n");
        }
        #endif
    }
    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

    // create grid_comm
    int ret = MPI_Cart_create(MPI_COMM_WORLD, 2, P_grid, wrap_around, reorder, &grid_comm);
    if (ret != MPI_SUCCESS){
        Debug("ERROR: MPI_Cart_create failed",1);
    }
    //get new rank and cartesian coords of this proc
    MPI_Comm_rank(grid_comm, &proc_rank);
    MPI_Cart_coords(grid_comm, proc_rank, 2, proc_coord);
    printf("(%i) (x,y)=(%i,%i)\n", proc_rank, proc_coord[X_DIR], proc_coord[Y_DIR]);
    //calc neighbours
    // MPI_Cart_shift(grid_comm, Y_DIR, 1, &proc_bottom, &proc_top);
    MPI_Cart_shift(grid_comm, Y_DIR, 1, &proc_top, &proc_bottom);
    MPI_Cart_shift(grid_comm, X_DIR, 1, &proc_left, &proc_right);
    printf("(%i) top %i,  right  %i,  bottom  %i,  left  %i\n", proc_rank, proc_top,
    proc_right, proc_bottom, proc_left);
}

void Setup_Grid()
```

```
208  {
209      int x, y, s;
210      double source_x, source_y, source_val;
211      FILE *f;
212
213      Debug("Setup_Subgrid", 0);
214
215      if(proc_rank == 0){
216          f = fopen("input.dat", "r");
217          if (f == NULL){
218              Debug("Error opening input.dat", 1);
219          }
220          fscanf(f, "nx: %i\n", &gridsize[X_DIR]);
221          fscanf(f, "ny: %i\n", &gridsize[Y_DIR]);
222          fscanf(f, "precision goal: %lf\n", &precision_goal);
223          fscanf(f, "max iterations: %i\n", &max_iter);
224      }
225      MPI_Bcast(&gridsize, 2, MPI_INT, 0, grid_comm);
226      MPI_Bcast(&precision_goal, 1, MPI_DOUBLE, 0, grid_comm);
227      MPI_Bcast(&max_iter, 1, MPI_INT, 0, grid_comm);
228      hx = 1 / (double)gridsize[X_DIR];
229      hy = 1 / (double)gridsize[Y_DIR];
230
231      /* Calculate dimensions of local subgrid */ //! We do that later now!
232      // dim[X_DIR] = gridsize[X_DIR] + 2;
233      // dim[Y_DIR] = gridsize[Y_DIR] + 2;
234
235      //! Step 7
236      int upper_offset[2] = {0,0};
237      // Calculate top left corner cordinates of local grid
238      offset[X_DIR] = gridsize[X_DIR] * proc_coord[X_DIR] / P_grid[X_DIR];
239      offset[Y_DIR] = gridsize[Y_DIR] * proc_coord[Y_DIR] / P_grid[Y_DIR];
240      upper_offset[X_DIR] = gridsize[X_DIR] * (proc_coord[X_DIR] + 1) / P_grid[X_DIR];
241      upper_offset[Y_DIR] = gridsize[Y_DIR] * (proc_coord[Y_DIR] + 1) / P_grid[Y_DIR];
242
243      // dimensions of local grid
244      dim[X_DIR] = upper_offset[X_DIR] - offset[X_DIR];
245      dim[Y_DIR] = upper_offset[Y_DIR] - offset[Y_DIR];
246      // Add space for rows/columns of neighboring grid
247      dim[X_DIR] += 2;
248      dim[Y_DIR] += 2;
249      //! Step 7 end
250
251      /* allocate memory */
252      if ((phi = malloc(dim[X_DIR] * sizeof(*phi))) == NULL){
253          Debug("Setup_Subgrid : malloc(phi) failed", 1);
254      }
255      if ((source = malloc(dim[X_DIR] * sizeof(*source))) == NULL){
256          Debug("Setup_Subgrid : malloc(source) failed", 1);
257      }
258      if ((phi[0] = malloc(dim[Y_DIR] * dim[X_DIR] * sizeof(**phi))) == NULL){
259          Debug("Setup_Subgrid : malloc(*phi) failed", 1);
260      }
261      if ((source[0] = malloc(dim[Y_DIR] * dim[X_DIR] * sizeof(**source))) == NULL){
262          Debug("Setup_Subgrid : malloc(*source) failed", 1);
263      }
264      for (x = 1; x < dim[X_DIR]; x++)
265      {
266          phi[x] = phi[0] + x * dim[Y_DIR];
267          source[x] = source[0] + x * dim[Y_DIR];
268      }
269
270      /* set all values to '0' */
271      for (x = 0; x < dim[X_DIR]; x++){
272          for (y = 0; y < dim[Y_DIR]; y++)
273          {
274              phi[x][y] = 0.0;
275              source[x][y] = 0;
276          }
277      }
278      /* put sources in field */
279      do{
280          if (proc_rank==0)
```

```
281            {
282                s = fscanf(f, "source: %lf %lf %lf\n", &source_x, &source_y, &source_val);
283            }
284        MPI_Bcast(&s, 1, MPI_INT, 0, grid_comm);
285        if (s==3){
286            MPI_Bcast(&source_x, 1, MPI_DOUBLE, 0, grid_comm);
287            MPI_Bcast(&source_y, 1, MPI_DOUBLE, 0, grid_comm);
288            MPI_Bcast(&source_val, 1, MPI_DOUBLE, 0, grid_comm);
289            x = source_x * gridsize[X_DIR];
290            y = source_y * gridsize[Y_DIR];
291            x = x + 1 - offset[X_DIR]; // Step 7 --> local grid transform
292            y = y + 1 - offset[Y_DIR]; // Step 7 --> local grid transform
293            if(x > 0 && x < dim[X_DIR] -1 && y > 0 && y < dim[Y_DIR]-1){ // check if in local
    grid
294                phi[x][y] = source_val;
295                source[x][y] = 1;
296            }
297        }
298    }
299    while (s==3);
300
301    if(proc_rank==0){
302        fclose(f);
303    }
304 }
305
306 void Setup_MPI_Datatypes()
307 {
308    Debug("Setup_MPI_Datatypes",0);
309
310    // vertical data exchange (Y_Dir)
311    MPI_Type_vector(dim[X_DIR] - 2, 1, dim[Y_DIR], MPI_DOUBLE, &border_type[Y_DIR]);
312    // horizontal data exchange (X_Dir)
313    MPI_Type_vector(dim[Y_DIR] - 2, 1, 1, MPI_DOUBLE, &border_type[X_DIR]);
314
315    MPI_Type_commit(&border_type[Y_DIR]);
316    MPI_Type_commit(&border_type[X_DIR]);
317 }
318
319 int Exchange_Borders()
320 {
321    #ifdef MONITOR_EXCHANGE_BORDERS
322    double start_time, latency_start, latency;
323    double data_size_top, data_size_left;
324    double exchange_time;
325
326    // Measure latency with a small dummy message
327    latency_start = MPI_Wtime();
328    double dummy;
329    MPI_Sendrecv(&dummy, 1, MPI_DOUBLE, proc_top, 0, &dummy, 1, MPI_DOUBLE, proc_bottom, 0,
    grid_comm, &status);
330    latency = MPI_Wtime() - latency_start;
331    total_latency += latency;
332
333    // Calculate data sizes
334    data_size_top = dim[X_DIR] * sizeof(double);  // Top and bottom rows
335    data_size_left = dim[Y_DIR] * sizeof(double); // Left and right columns
336    double data_transferred = 2 * (data_size_top + data_size_left); // Total data for this
    exchange
337    total_data_transferred += data_transferred;
338    #endif
339
340    Debug("Exchange_Borders",0);
341    #ifdef MONITOR_EXCHANGE_BORDERS
342    start_time = MPI_Wtime();
343    #endif
344    // top direction
345    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);
346    // bottom direction
347    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);
348    // left direction
```

```
349    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);
350    // right direction
351    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);
352
353    #ifdef MONITOR_EXCHANGE_BORDERS
354    exchange_time = MPI_Wtime() - start_time;
355    total_exchange_time += exchange_time;
356    num_exchanges++;
357    #endif
358    return 1;
359 }
360
361 double Do_Step(int parity)
362 {
363    int x, y;
364    double old_phi, c_ij;
365    double max_err = 0.0;
366
367    #ifdef FAST_DO_STEP_LOOP
368    int start_y;
369    for (x = 1; x < dim[X_DIR] - 1; x++){
370        start_y = ((1 + x + offset[X_DIR] + offset[Y_DIR]) % 2 == parity) ? 1 : 2;
371        for (y = start_y; y < dim[Y_DIR] - 1; y += 2){
372            if (source[x][y] != 1){
373                old_phi = phi[x][y];
374                #ifndef SOR
375                phi[x][y] = (phi[x + 1][y] + phi[x - 1][y] + phi[x][y + 1] + phi[x][y - 1]) *
       0.25;
376                #endif
377                #ifdef SOR
378                c_ij = (phi[x + 1][y] + phi[x - 1][y] + phi[x][y + 1] + phi[x][y - 1] + hx*hy*
       source[x][y]) * 0.25 - phi[x][y];
379                phi[x][y] += sor_omega*c_ij;
380                #endif
381                if (max_err < fabs(old_phi - phi[x][y])){
382                    max_err = fabs(old_phi - phi[x][y]);
383                }
384            }
385        }
386    }
387    return max_err;
388    #endif
389
390    #ifndef FAST_DO_STEP_LOOP
391    /* calculate interior of grid */
392    for (x = 1; x < dim[X_DIR] - 1; x++){
393        for (y = 1; y < dim[Y_DIR] - 1; y++){
394            if ((x + offset[X_DIR] + y + offset[Y_DIR]) % 2 == parity && source[x][y] != 1){
395                old_phi = phi[x][y];
396                #ifndef SOR
397                phi[x][y] = (phi[x + 1][y] + phi[x - 1][y] + phi[x][y + 1] + phi[x][y - 1]) *
       0.25;
398                #endif
399                #ifdef SOR
400                c_ij = (phi[x + 1][y] + phi[x - 1][y] + phi[x][y + 1] + phi[x][y - 1] + hx*hy*
       source[x][y]) * 0.25 - phi[x][y];
401                phi[x][y] += sor_omega*c_ij;
402                #endif
403                if (max_err < fabs(old_phi - phi[x][y])){
404                    max_err = fabs(old_phi - phi[x][y]);
405                }
406            }
407        }
408    }
409    return max_err;
410    #endif
411 }
412
413 void Solve()
414 {
415    int count = 0;
```

```
416    double delta;
417    double global_delta;
418    double delta1, delta2;
419
420    Debug("Solve", 0);
421
422    /* give global_delta a higher value then precision_goal */
423    global_delta = 2 * precision_goal;
424
425    while (global_delta > precision_goal && count < max_iter)
426    {
427        Debug("Do_Step 0", 0);
428        delta1 = Do_Step(0);
429        #ifdef SKIP_EXCHANGE
430        if (count % skip_exchange == 0 && Exchange_Borders()) // use short circuit evaluation
431        #endif
432        #ifndef SKIP_EXCHANGE
433        Exchange_Borders();
434        #endif
435        Debug("Do_Step 1", 0);
436        delta2 = Do_Step(1);
437        #ifdef SKIP_EXCHANGE
438        if (count % skip_exchange == 0 && Exchange_Borders())
439        #endif
440        #ifndef SKIP_EXCHANGE
441        Exchange_Borders();
442        #endif
443        delta = max(delta1, delta2);
444        #ifdef MONITOR_ALLREDUCE
445        double time_ = MPI_Wtime();
446        #endif
447        #ifdef ALLREDUCE_COUNT
448        if(count % ALLREDUCE_COUNT == 0){
449            MPI_Allreduce(&delta, &global_delta, 1, MPI_DOUBLE, MPI_MAX, grid_comm);
450        }
451        #endif
452        #ifndef ALLREDUCE_COUNT
453        MPI_Allreduce(&delta, &global_delta, 1, MPI_DOUBLE, MPI_MAX, grid_comm);
454        #endif
455        #ifdef MONITOR_ALLREDUCE
456        all_reduce_time += MPI_Wtime() - time_;
457        #endif
458        #ifdef MONITOR_ERROR
459        if (proc_rank == 0)
460        {
461            errors[count] = global_delta;
462        }
463        #endif
464        count++;
465    }
466
467    printf("(%i) Number of iterations : %i\n", proc_rank, count);
468    #ifdef MONITOR_ALLREDUCE
469    printf("(%i) Allreduce time: %14.6f\n", proc_rank, all_reduce_time);
470    #endif
471    #ifdef MONITOR_EXCHANGE_BORDERS
472    printf("(%i) Exchange time: %14.6f\n", proc_rank, total_exchange_time);
473    #endif
474 }
475
476 double* get_Global_Grid()
477 {
478    Debug("get_Global_Grid", 0);
479    //!! DEBUG only
480    for (size_t i = 0; i < dim[X_DIR]; i++)
481    {
482        for (size_t j = 0; j < dim[Y_DIR]; j++)
483        {
484            phi[i][j] = proc_rank;
485        }
486
487    }
488
```

```
489        // only process 0 needs to store all data!
490        double* global_phi = NULL;
491        if (proc_rank == 0) {
492            global_phi = malloc(gridsize[X_DIR] * gridsize[Y_DIR] * sizeof(double));
493            if (global_phi == NULL) {
494                Debug("get_Global_Grid : malloc(global_phi) failed", 1);
495            }
496        }
497
498        // copy own part into buffer - flatten!
499        size_t buf_size = (dim[X_DIR] - 2) * (dim[Y_DIR] - 2) * sizeof(double);
500        double* local_phi = malloc(buf_size);
501        int idx = 0;
502        for (int x = 1; x < dim[X_DIR] - 1; x++) {
503            for (int y = 1; y < dim[Y_DIR] - 1; y++) {
504                local_phi[idx++] = phi[x][y];
505            }
506        }
507        printf("I'm proc %d and i have a buffer of size %zu\n", proc_rank, buf_size);
508
509
510        // only proc 0 needs sendcounts and displacements for the gatherv operation
511        int* sendcounts = NULL;
512        int* displs = NULL;
513        if (proc_rank == 0) {
514            sendcounts = malloc(P * sizeof(int));
515            displs = malloc(P * sizeof(int));
516
517            // size and offset of different subgrids
518            //! Note that this only works if every process has the same subgrid
519            if (gridsize[X_DIR] % P_grid[X_DIR] != 0 || gridsize[Y_DIR] % P_grid[Y_DIR] != 0)
520            {
521                Debug("!!!A grid dimension is not a multiple of the P_grid in this direction!", 1)
       ;
522            }
523
524            int subgrid_width = gridsize[X_DIR] / P_grid[X_DIR];
525            int subgrid_height = gridsize[Y_DIR] / P_grid[Y_DIR];
526            for (int px = 0; px < P_grid[X_DIR]; px++) {
527                for (int py = 0; py < P_grid[Y_DIR]; py++) {
528                    int rank = px * P_grid[Y_DIR] + py;
529                    sendcounts[rank] = subgrid_width * subgrid_height;
530                    displs[rank] = (px * subgrid_width * gridsize[Y_DIR]) + (py * subgrid_height);
531                }
532            }
533        }
534        Debug("get_Global_Grid : MPI_Gatherv", 0);
535        //! TODO this Gatherv does something wrong - all local grids are alright!!!
536        MPI_Gatherv(local_phi, (dim[X_DIR] - 2) * (dim[Y_DIR] - 2), MPI_DOUBLE, global_phi,
       sendcounts, displs, MPI_DOUBLE, 0, MPI_COMM_WORLD);
537
538        free(local_phi);
539        if (proc_rank == 0) {
540            free(sendcounts);
541            free(displs);
542        }
543
544        return global_phi;
545    }
546
547    void Write_Grid_global(){
548        int x, y;
549        FILE *f;
550        char filename[40]; //seems danagerous to use a static buffer but let's go with the steps
551        sprintf(filename, "output_MPI_global_%i.dat", proc_rank);
552        if ((f = fopen(filename, "w")) == NULL){
553            Debug("Write_Grid : fopen failed", 1);
554        }
555
556        Debug("Write_Grid", 0);
557
558        for (x = 1; x < dim[X_DIR]-1; x++){
559            for (y = 1; y < dim[Y_DIR]-1; y++){
```

```c
560              int x_glob = x + offset[X_DIR];
561              int y_glob = y + offset[Y_DIR];
562              fprintf(f, "%i %i %f\n", x_glob, y_glob, phi[x][y]);
563          }
564      }
565      fclose(f);
566  }
567
568  void Write_Grid()
569  {
570      double* global_phi = get_Global_Grid();
571      if(proc_rank != 0){
572          assert (global_phi == NULL);
573          return;
574      }
575      int x, y;
576      FILE *f;
577      char filename[40]; //seems danagerous to use a static buffer but let's go with the steps
578      sprintf(filename, "output_MPI%i.dat", proc_rank);
579      if ((f = fopen(filename, "w")) == NULL){
580          Debug("Write_Grid : fopen failed", 1);
581      }
582
583      Debug("Write_Grid", 0);
584
585      for (x = 0; x < gridsize[X_DIR]; x++){
586          for (y = 0; y < gridsize[Y_DIR]; y++){
587              fprintf(f, "%i %i %f\n", x+1, y+1, global_phi[x*gridsize[Y_DIR] + y]);
588          }
589      }
590      fclose(f);
591      free(global_phi);
592  }
593
594  void Clean_Up()
595  {
596      Debug("Clean_Up", 0);
597
598      free(phi[0]);
599      free(phi);
600      free(source[0]);
601      free(source);
602      #ifdef MONITOR_ERROR
603      free(errors);
604      #endif
605  }
606  void setup_error_monitor(){
607      if (proc_rank != 0)
608      {
609          return;
610      }
611
612      errors = malloc(sizeof(double)*max_iter);
613  }
614  void write_errors(){
615      if(proc_rank != 0){
616          return;
617      }
618      FILE *f;
619      char filename[40]; //seems danagerous to use a static buffer but let's go with the steps
620      sprintf(filename, "errors_MPI.dat");
621      if ((f = fopen(filename, "w")) == NULL){
622          Debug("Write_Errors : fopen failed", 1);
623      }
624
625      Debug("Write_Errors", 0);
626
627      for (size_t i = 0; i < max_iter; ++i)
628      {
629          fprintf(f, "%f\n", errors[i]);
630      }
631      fclose(f);
632  }
```

```c
633
634  void Print_Aggregated_Metrics()
635  {
636      #ifdef MONITOR_EXCHANGE_BORDERS
637      if (num_exchanges > 0) {
638          double avg_exchange_time = total_exchange_time / num_exchanges;
639          double avg_latency = total_latency / num_exchanges;
640          double avg_bandwidth = total_data_transferred / total_exchange_time;
641
642          printf("\n--- Aggregated Metrics ---\n");
643          printf("Total Exchanges: %d\n", num_exchanges);
644          printf("Total Data Transferred: %.2f bytes\n", total_data_transferred);
645          printf("Total Exchange Time: %.9f s\n", total_exchange_time);
646          printf("Average Exchange Time per Call: %.9f s\n", avg_exchange_time);
647          printf("Average Latency per Call: %.9f s\n", avg_latency);
648          printf("Average Bandwidth: %.2f bytes/s\n", avg_bandwidth);
649      } else {
650          printf("No exchanges recorded.\n");
651      }
652      #endif
653  }
654
655  int main(int argc, char **argv)
656  {
657      MPI_Init(&argc, &argv);
658      Setup_Proc_Grid(argc,argv); // was earlier MPI_Comm_rank(MPI_COMM_WORLD, &proc_rank);
659      start_timer();
660
661      Setup_Grid();
662      Setup_MPI_Datatypes();
663
664      #ifdef SOR
665      if (proc_rank == 0)
666      {
667          printf("SOR using omega: %.5f\n", sor_omega);
668      }
669      #endif
670      #ifdef MONITOR_ERROR
671      setup_error_monitor();
672      #endif
673
674      Solve();
675      #ifdef MONITOR_ERROR
676      write_errors();
677      #endif
678      // Write_Grid();
679      Write_Grid_global();
680      Print_Aggregated_Metrics();
681      print_timer();
682
683      Clean_Up();
684      MPI_Finalize();
685      return 0;
686  }
```