OpenMP and MPI parallelization

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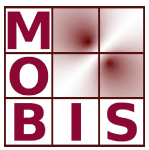

OpenMP for our example

OpenMP generation in code

- Determine matrix pattern and allocate memory for CRS

```
Get_Matrix_Pattern(nelem, 3, ia, nnz, id, ik, sk);
```

  remains sequential, only once needed
- Calculate Matrix entries and accumulate them

```
GetMatrix (nelem, 3, ia, nnode, xc, nnz, id, ik, sk, f);
```

  Parallel loop over all elements: `#pragma omp parallel for`
  `#pragma omp atomic` needed in accumulation
- Apply Dirichlet boundary conditions

```
ApplyDirichletBC(nx, ny, neigh, u, id, ik, sk, f);
```

  remains sequential

Jacobi iteration

We solve $K\underline{u} = f$ by the Jacobi iteration ($\omega = 1$)

$$\underline{u}^{k+1} := \underline{u}^{k+1} + \omega D^{-1}\left(\underline{f} - K \cdot \underline{u}^{k}\right)$$

```
JacobiSolve(nnode, id, ik, sk, f, u );
```

$D := \mathrm{diag}(K)$ // #pragma omp parallel for
$\underline{u} := 0$
$\underline{r} := \underline{f} - K \cdot \underline{u}^0$
$\underline{w} := D^{-1} \cdot \underline{r}$
$\sigma := \sigma_0 := (\underline{w}, \underline{r})$
$k := 0$
while $\sigma > \varepsilon^2 \cdot \sigma_0$ do
  $k := k + 1$
  $\underline{u}^k := \underline{u}^{k-1} + \omega \cdot \underline{w}$ // #pragma omp parallel for
  $\underline{r} := \underline{f} - K \cdot \underline{u}^k$ // #pragma omp parallel for
  $\underline{w} := D^{-1} \cdot \underline{r}$ // #pragma omp parallel for
  $\sigma := (\underline{w}, \underline{r})$ // #pragma omp parallel for reduction
end

OpenMP compiling

- Compile/Link: `g++ -fopenmp *.cpp -o main.GCC_`
- Set the number of parallel threads for the run:
  `export OMP_NUM_THREADS 2`
- run: `./main.GCC_`
- The number of threads can programmed into the code the code explicitely:
  `omp_set_num_threads(2);` or via a clause in an OMP-pragma directive.
- Code examples in *shm*.

MPI for our example

6+6 basic functions in MPI

Basic functions	MPI_Init
	MPI_Finalize
	MPI_Send
	MPI_Recv
	MPI_Comm_rank
	MPI_Comm_size
	MPI_Barrier
	MPI_Bcast
	MPI_Gather
	MPI_Scatter
	MPI_Reduce
	MPI_Allreduce

Start MPI

We only determine rank and number of processes.

```
1  #include <mpi.h>                    // MPI
2
3  int main(int argc, char **argv)
4
5  {
6    MPI_Comm icomm = MPI_COMM_WORLD;     // take all MPI processes
7    int myrank, numprocs;                // my MPI-rank; number of MPI process
8
9    MPI_Init(&argc,&argv);               // start parallel MPI code
10
11   MPI_Comm_rank(icomm, &myrank);       // get my rank
12   MPI_Comm_size(icomm, &numprocs);     // get number of processes
13
14   cout << "MPI process " << myrank << " out of " << numprocs << endl;
15   MPI_Barrier(icomm); fflush(stdout); MP_Barrier(icomm);
16
17   MPI_Finalize();                       // end parallel MPI code
18
19   return 0;
20 }
```

```
mpicxx main.cpp -o main.GCC_
mpirun -np 2 ./main.GCC_
```

Point-to-point communication: Data exchange I

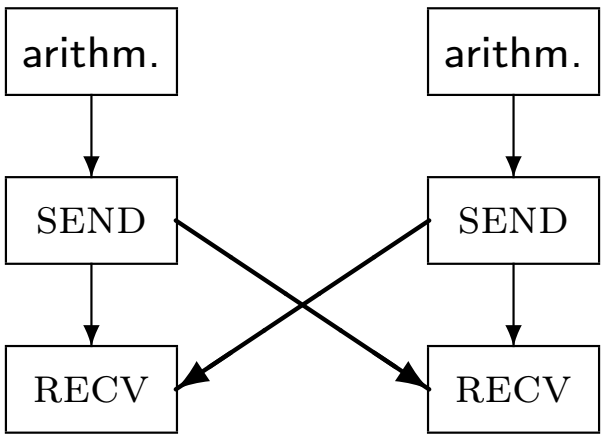

Figure: Non-synchronized EXCHANGE

Point-to-point communication: Data exchange II

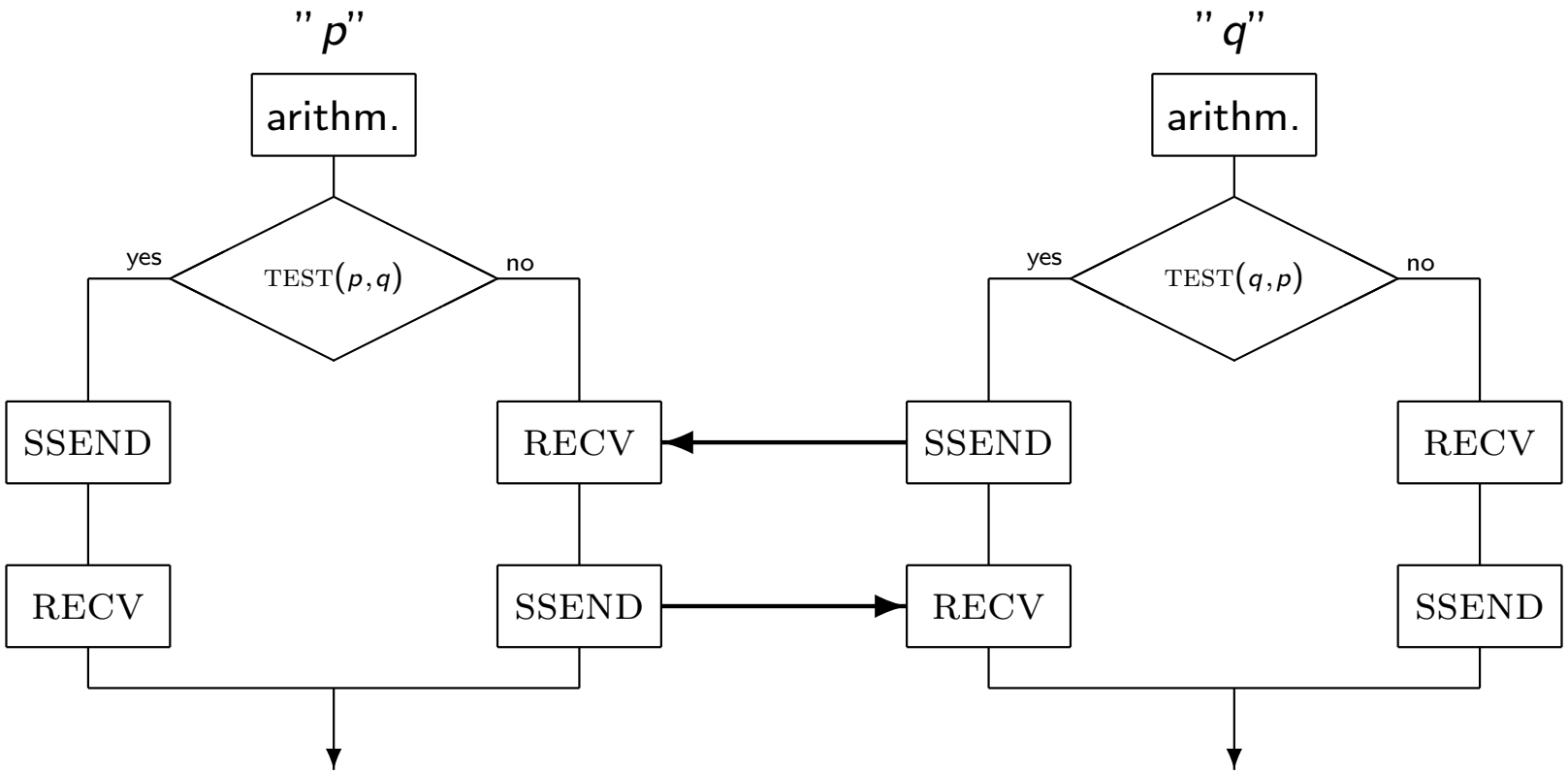

Figure: Synchronized EXCHANGE

A synchronized send SSEND stops execution until the receiving process returns a receipt. If that process also waits for a receipt $\Longrightarrow$ **dead lock**.

Collective operations: Gather and Scatter

Collect and distribute information from a **root** process to all processs (including the root itself)

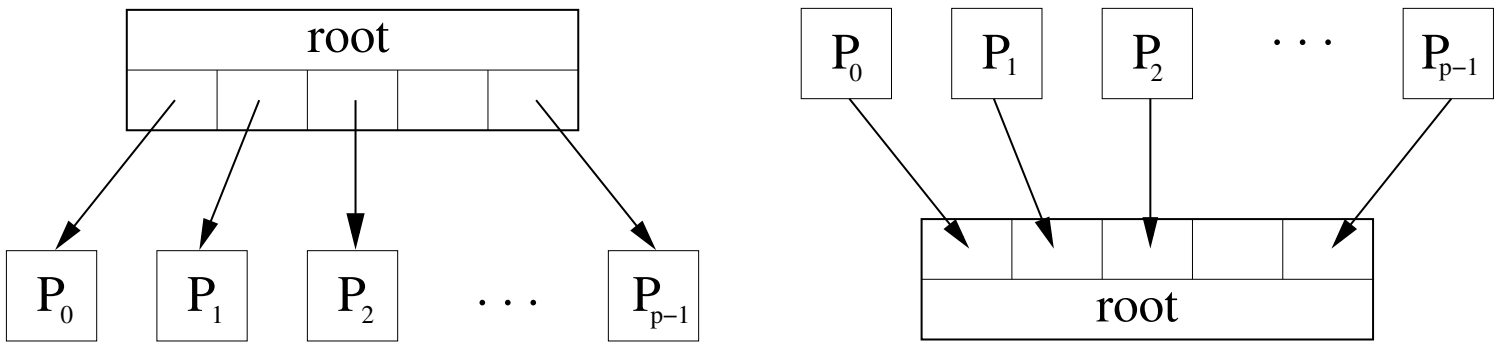

Figure: SCATTER and GATHER

- Classically: The size of data for eacxh process is the same
- A pile of special gather/scatter operations exists also with individual data sizes
- ALL_ versions exist where all processes function a sroot.

Broadcast

One root process send the identicak data to all processes.
This is just a special scatter.

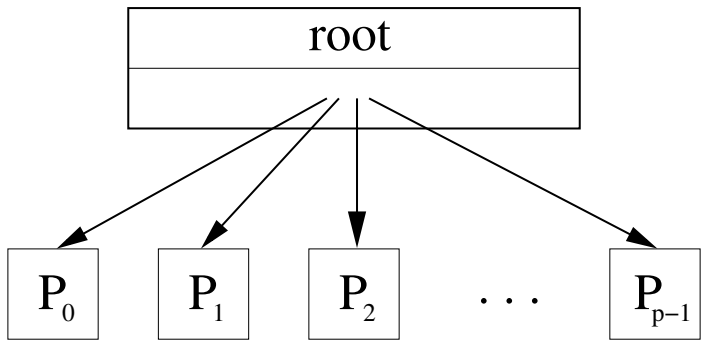

Figure: BROADCAST operation

Reduce and Reduce-all operation

Individual data from the processes will be combined to a global result, available to root or to all processes.

Inner product: $\langle \mathfrak{w}, \mathsf{r} \rangle = \sum_{i=1}^{P} \langle \mathfrak{w}_i, \mathsf{r}_i \rangle$

```
#include <mpi.h>                    // MPI

float skalar(const int n, const float x[], const float y[], const MPI_Comm icomm)
{
  const float s = dscapr(n,x,y);                // call sequential inner product
        float sg;
  MPI_Allreduce(&s, &sg, 1, MPI_FLOAT, MPI_SUM, icomm);
  return(sg);
}
```

- You have to specify the data type (MPI_FLOAT) and the type of operation (MPI_SUM)
- An input array (s) and an output array (sg) have to be allocated.
- Here, the arrays have length 1.

MPI parallel Jacobi iteration

$$
\begin{array}{lll}
\mathfrak{D} & := & \sum_{s=1}^{P} A_s^T \operatorname{diag}(K_s) A_s \qquad \text{// next neighbor comm.: VecAccu} \\
\underline{\mathfrak{u}} & := & 0 \\
\underline{r} & := & \underline{f} - K \cdot \underline{\mathfrak{u}}^0 \\
\underline{\mathfrak{w}} & := & \mathfrak{D}^{-1} \cdot \sum_{s=1}^{P} A_s^T \underline{r}_s \qquad \text{// next neighbor comm.: VecAccu} \\
\sigma & := & \sigma_0 := (\underline{\mathfrak{w}}, \underline{r}) \qquad \text{// parallel reduction: MPI\_Allreduce} \\
k & := & 0 \\
\text{while} & \sigma > \varepsilon^2 \cdot \sigma_0 & \text{do} \\
& k & := k+1 \\
& \underline{\mathfrak{u}}^k & := \underline{\mathfrak{u}}^{k-1} + \omega \cdot \underline{\mathfrak{w}} \qquad \text{// no comm.} \\
& \underline{r} & := \underline{f} - K \cdot \underline{\mathfrak{u}}^k \qquad \text{// no comm.} \\
& \underline{\mathfrak{w}} & := \mathfrak{D}^{-1} \cdot \sum_{s=1}^{P} A_s^T \underline{r}_s \qquad \text{// next neighbor comm.: VecAccu} \\
& \sigma & := (\underline{\mathfrak{w}}, \underline{r}) \qquad \text{// parallel reduction: MPI\_Allreduce} \\
\text{end} & & \\
\end{array}
$$

See MPI-template code in *par*, MPI solutions in *Cxx.Solution*.