

## Parallel Numerics

### Exercise 6: Tridiagonal Matrices, Hockney/Golub method & Message Tags

#### 1) Block-wise Gaussian Elimination for Tridiagonal Matrices

The solution of a linear equation system

$$Ax = d$$

with a tridiagonal matrix  $A \in \mathbb{R}^{n \times n}$  and  $d \in \mathbb{R}^n$  should be calculated. The notation is as follows:

$$A = \begin{pmatrix} b_1 & c_1 & & & & & & & & \\ a_2 & b_2 & c_2 & & & & & & & \mathbf{0} \\ & a_3 & b_3 & c_3 & & & & & & \mathbf{0} \\ & & & \ddots & \ddots & \ddots & & & & \\ & \mathbf{0} & & a_{n-1} & b_{n-1} & c_{n-1} & & & & \\ & & & & a_n & b_n & & & & \end{pmatrix}, \quad d = \begin{pmatrix} d_1 \\ d_2 \\ \vdots \\ d_{n-1} \\ d_n \end{pmatrix}, \quad x = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_{n-1} \\ x_n \end{pmatrix}$$

- i) Examine the behaviour of a parallel Gaussian Elimination that assigns the columns cyclically to the different nodes of a parallel computer. What is an optimal number of nodes  $p$ ?
- ii) Split up the rows of  $A$  into  $p$  blocks. Derive the sparsity pattern and the fill-ins for the following algorithm:
  1. In the first step elements of lower subdiagonal are eliminated by addition of an appropriate multiple of the first row of each partition. There are no dependencies between the partitions.
  2. In the second step elements of the upper side diagonal are eliminated in a similar way: By addition of a suitable multiple of the second line from below of each partition to the rows above this row all these elements disappear but the one in the last row. For the elimination of this one the modified first row of the lower neighbouring partition is used. Note that only the elimination of the last element of each partition depends on the results of the elimination process of another partition.
  3. In the third step the elements below the main diagonal are eliminated. This is done by addition of an appropriate multiple of the last row of the upper neighbouring partition to each row of the partition; the first partition is skipped naturally. This is how the elimination processes of the single partitions are connected here.

4. Finally the elements in the upper part are removed. Each partition uses its last row, whose nondiagonal element is eliminated by addition of a suitable multiple of the last row of the lower neighbouring partition. Again the elimination processes depend on each other only through the the elimination of a single element.

iii) Implement the algorithm.

## 2) MPI Message Tags

Given is the following send process running on p0:

```
int a=1;
int b=2;
int c=3;
MPI_Send(&a,1,MPI_INT,p1,0,MPI_COMM_WORLD);
MPI_Send(&b,1,MPI_INT,p1,0,MPI_COMM_WORLD);
MPI_Send(&c,1,MPI_INT,p1,1,MPI_COMM_WORLD);
```

- i) What is the result of the following receive code fragment running on p1?

```
int u;
int v;
int w;
MPI_Recv(&u,1,MPI_INT,p0,0,MPI_COMM_WORLD);
MPI_Recv(&v,1,MPI_INT,p0,0,MPI_COMM_WORLD);
MPI_Recv(&w,1,MPI_INT,p0,0,MPI_COMM_WORLD);
```

- ii) What is the result of the following receive code fragment running on p1?

```
int u;
int v;
int w;
MPI_Recv(&u,1,MPI_INT,p0,0,MPI_COMM_WORLD);
MPI_Recv(&v,1,MPI_INT,p0,1,MPI_COMM_WORLD);
MPI_Recv(&w,1,MPI_INT,p0,0,MPI_COMM_WORLD);
```

### 3) The Hockney/Golub Method

Again, the solution of a tridiagonal linear equation system should be calculated. With  $N := \lceil \log_2 n \rceil$  and the definitions

$$\begin{aligned} a_i^{(0)} &:= a_i, \quad i = 2, \dots, n, & a_1^{(0)} &:= 0 \\ b_i^{(0)} &:= b_i, \quad i = 1, \dots, n, \\ c_i^{(0)} &:= c_i, \quad i = 1, \dots, n-1, & c_n^{(0)} &:= 0 \\ d_i^{(0)} &:= d_i, \quad i = 1, \dots, n, \\ a_i^{(k)} &:= c_i^{(k)} := d_i^{(k)} := 0, & b_i^{(k)} &:= 1 \\ && \text{for } i \in \mathbb{Z} \setminus \{1, \dots, n\}, & k = 0, \dots, N \end{aligned}$$

the values  $a_i^{(k)}, b_i^{(k)}, c_i^{(k)}, d_i^{(k)}$  are calculated recursively:

$$\begin{aligned} a_i^{(k)} &:= \alpha_i^{(k-1)} a_{i-2^{k-1}}^{(k-1)} \\ c_i^{(k)} &:= \gamma_i^{(k-1)} c_{i+2^{k-1}}^{(k-1)} \\ b_i^{(k)} &:= \alpha_i^{(k-1)} c_{i-2^{k-1}}^{(k-1)} + b_i^{(k-1)} + \gamma_i^{(k-1)} a_{i+2^{k-1}}^{(k-1)} \\ d_i^{(k)} &:= \alpha_i^{(k-1)} d_{i-2^{k-1}}^{(k-1)} + d_i^{(k-1)} + \gamma_i^{(k-1)} d_{i+2^{k-1}}^{(k-1)} \end{aligned}$$

with

$$\begin{aligned} \alpha_i^{(k-1)} &:= -a_i^{(k-1)} / b_{i-2^{k-1}}^{(k-1)} \\ \gamma_i^{(k-1)} &:= -c_i^{(k-1)} / b_{i+2^{k-1}}^{(k-1)} \end{aligned}$$

Then the following equation is valid for  $i \in \mathbb{Z}$ :

$$a_i^{(k)} x_{i-2^k} + b_i^{(k)} x_i + c_i^{(k)} x_{i+2^k} = d_i^{(k)}$$

The Hockney/Golub method uses this formula to calculate the solution of the linear system and can be applied in the following way:

1. Calculate the values  $a_i^{(k)}, b_i^{(k)}, c_i^{(k)}, d_i^{(k)}$  for  $k = 1, \dots, N, i = 1, \dots, n$ .
2. Calculate  $x_i = d_i^{(N)} / b_i^{(N)}$  for  $i = 1, \dots, n$ .

Understand and implement this algorithm! Compare this method to the Gaussian elimination method! Why can the Hockney/Golub method be advantageous?