

Parallel Computing

环境

- **OS:** *Ubuntu 18.04.2 LTS (GNU/Linux 4.18.0-21-generic x86_64)*
- **physical processor:** 2
- **cores / processor:** 14
- **库:** `OpenMp`, `MPI`, `Eigen`, `OpenGL`

1. 稀疏矩阵求解

实现一个“大规模稀疏矩阵的Conjugate Gradient(共轭梯度)求解器”，即，求解 $Ax = b$ 中的 x ，其中 A 为一个大型、稀疏矩阵。

1.1 代码设计及优化

使用高性能矩阵运算库Eigen实现对矩阵的运算加速。对 A , x , b 的初始化定义如下：

```
VectorXd x = VectorXd::Ones(MSIZE);  
VectorXd b = VectorXd::Ones(MSIZE);  
SpMat A = generateSparseMat(MSIZE);
```

共轭梯度求解器定义：

```
ConjugateGradient<SpMat, Lower|Upper> cg;  
// total iterations  
cg.setMaxIterations(MSIZE*10);  
// tolerance  
cg.setTolerance(1e-3);
```

实现并行计算代码如下：

```

void ParallelProcess(SpMat A, VectorXd x, VectorXd b, int core_num) {
    initParallel();
    // core numbers
    setNbThreads(core_num);
    cout<<"Parallel processing with "<<nbThreads()<<" cores...\n";
    auto start = chrono::steady_clock::now();
    // solve
    cg.compute(A);
    x = cg.solve(b);
    auto end = chrono::steady_clock::now();
    cout<<"Total iteration: "<<cg.iterations()<<endl;
    cout<<"Estimated error: "<<cg.error()<<endl;
    cout<<"Time elapsed: "
        << chrono::duration_cast<chrono::milliseconds>(end-start).count()
        <<" ms"<<endl<<endl;
}

```

1.2 运行结果

运行：在终端该文件夹运行 `make` 。

- 1000维稀疏矩阵运行结果：

```

Matrix size: 1000
Generating sparse matrix...
Parallel processing with 28 cores...
Total iteration: 2262
Estimated error: 0.000696779
Time elapsed: 1294 ms

Sequential processing with 1 core...
Total iteration: 2262
Estimated error: 0.000696779
Time elapsed: 11533 ms

Parallel processing with 2 cores...
Total iteration: 2262
Estimated error: 0.000696779
Time elapsed: 6080 ms

Parallel processing with 4 cores...
Total iteration: 2262
Estimated error: 0.000696779
Time elapsed: 3344 ms

Parallel processing with 8 cores...
Total iteration: 2262
Estimated error: 0.000696779
Time elapsed: 2009 ms

```

- 10000维稀疏矩阵运行结果：

```
(base) sjy1203@dell-Precision-7920-Towe
Matrix size: 10000
Generating sparse matrix...
Parallel processing with 28 cores...
Total iteration: 15769
Estimated error: 0.000994606
Time elapsed: 507962 ms

    }

Parallel processing with 8 cores...
Total iteration: 15769
Estimated error: 0.000994606
Time elapsed: 1099224 ms
```

1.3 分析

并行计算下多核的计算能力远远超过了串行计算的效率，28核计算1000维稀疏矩阵需要1秒而串行则需要12秒。当然计算耗时和核数并不是成线性的，这与核数增加之后进程通信开销增加等都有关系，结果符合预期。

2. Mandelbrot并行化

将分形算法用OpenMP并行化。

2.1 代码设计及优化

OpenMP实现并行化与算法的分离使得使用特别简易，可读性也很好。如下例子：

```
/* Define pseudocolor maps, ramps for red and blue,
   random for green */
#pragma omp parallel for num_threads(num_trds)
for (i=0; i<256; i++)
{
    redmap[i]=i/255.;
    greenmap[i]=drand48();
    bluemap[i]=1.0-i/255.;
}
```

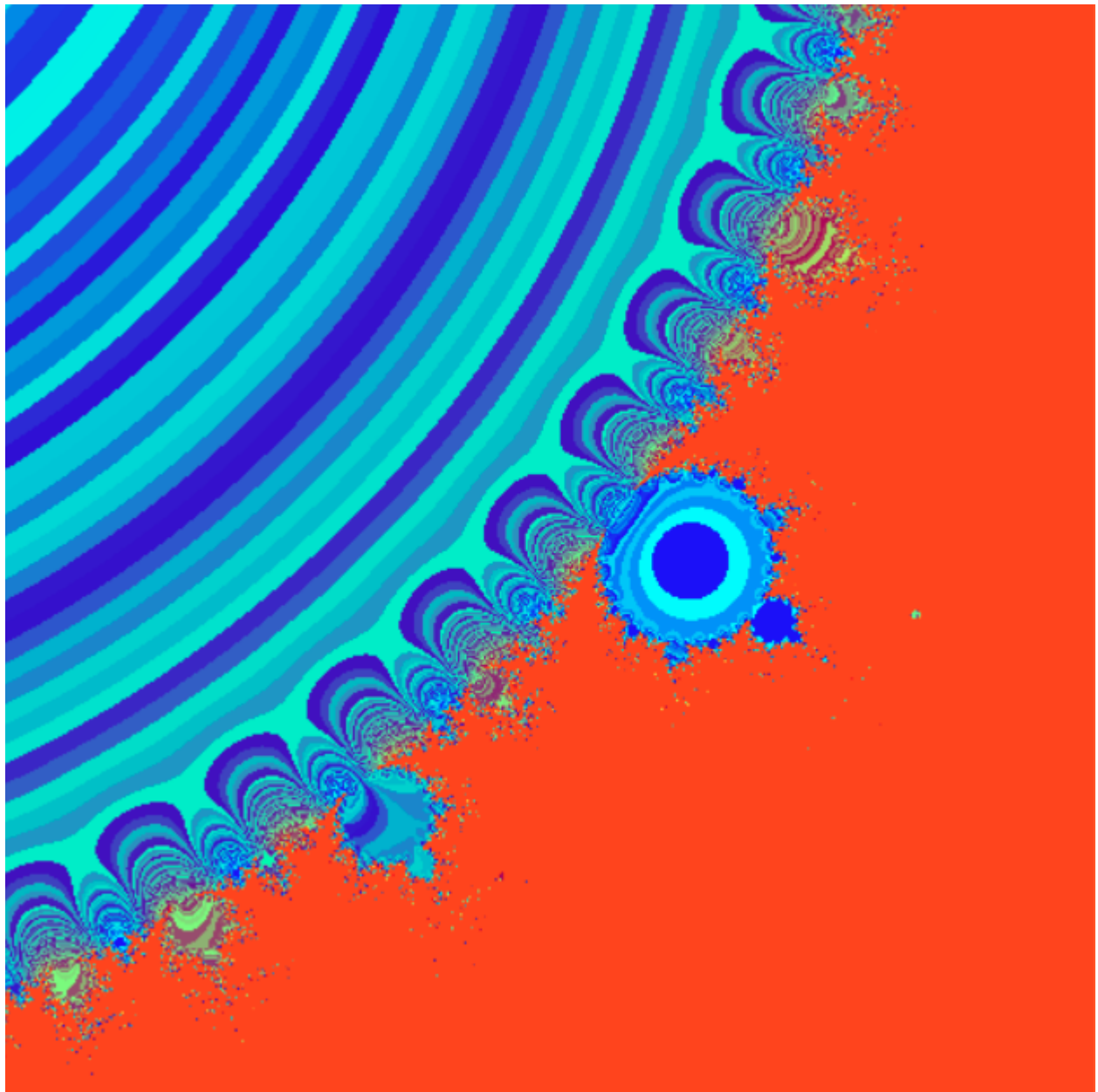
2.2 运行结果

运行：在终端该文件夹运行 `make`。

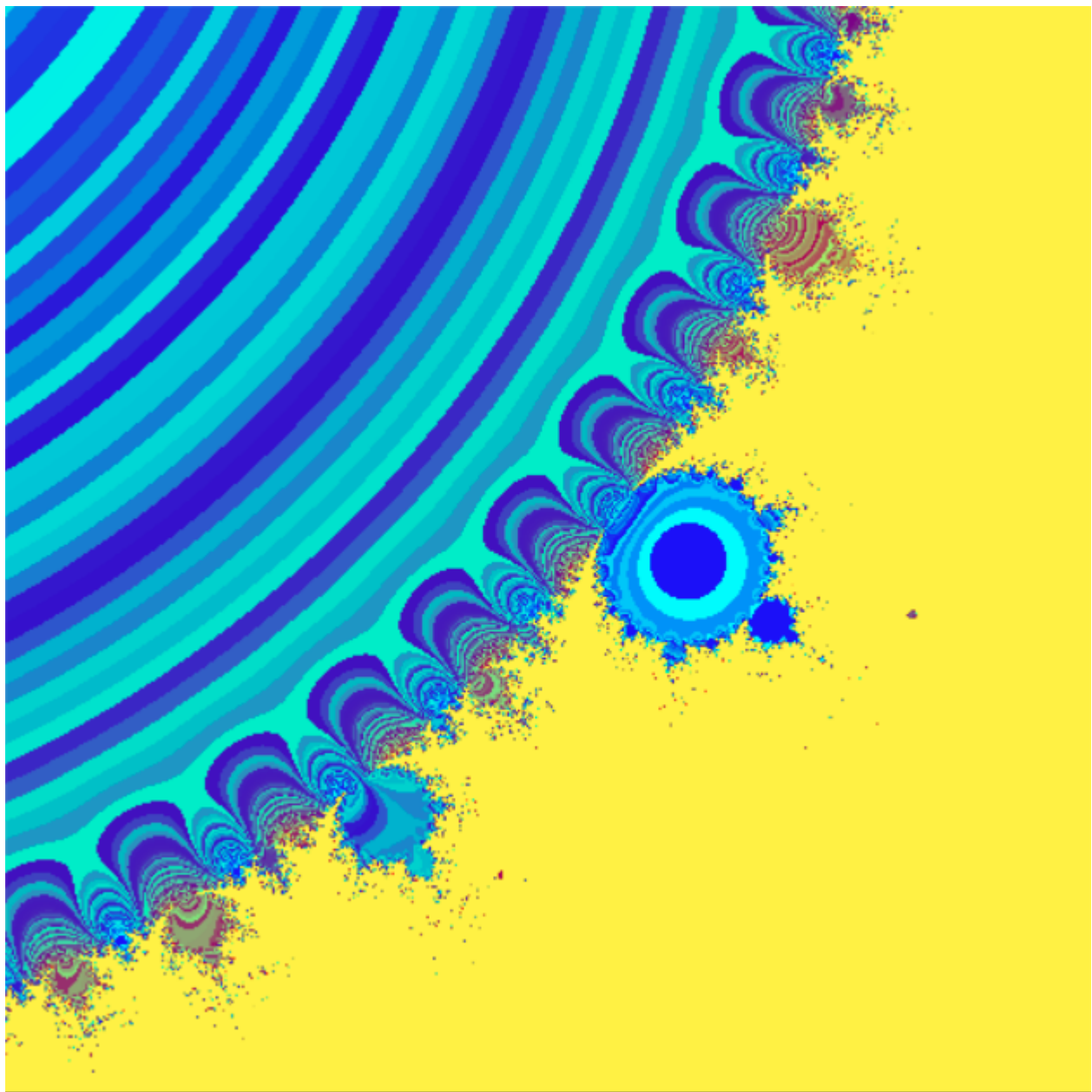
- 运行时间对比：

```
Core numbers: 1  
Elapsed time: 2104.88 ms  
  
Core numbers: 2  
Elapsed time: 2043.84 ms  
  
Core numbers: 4  
Elapsed time: 1864.31 ms  
  
Core numbers: 8  
Elapsed time: 1674.32 ms
```

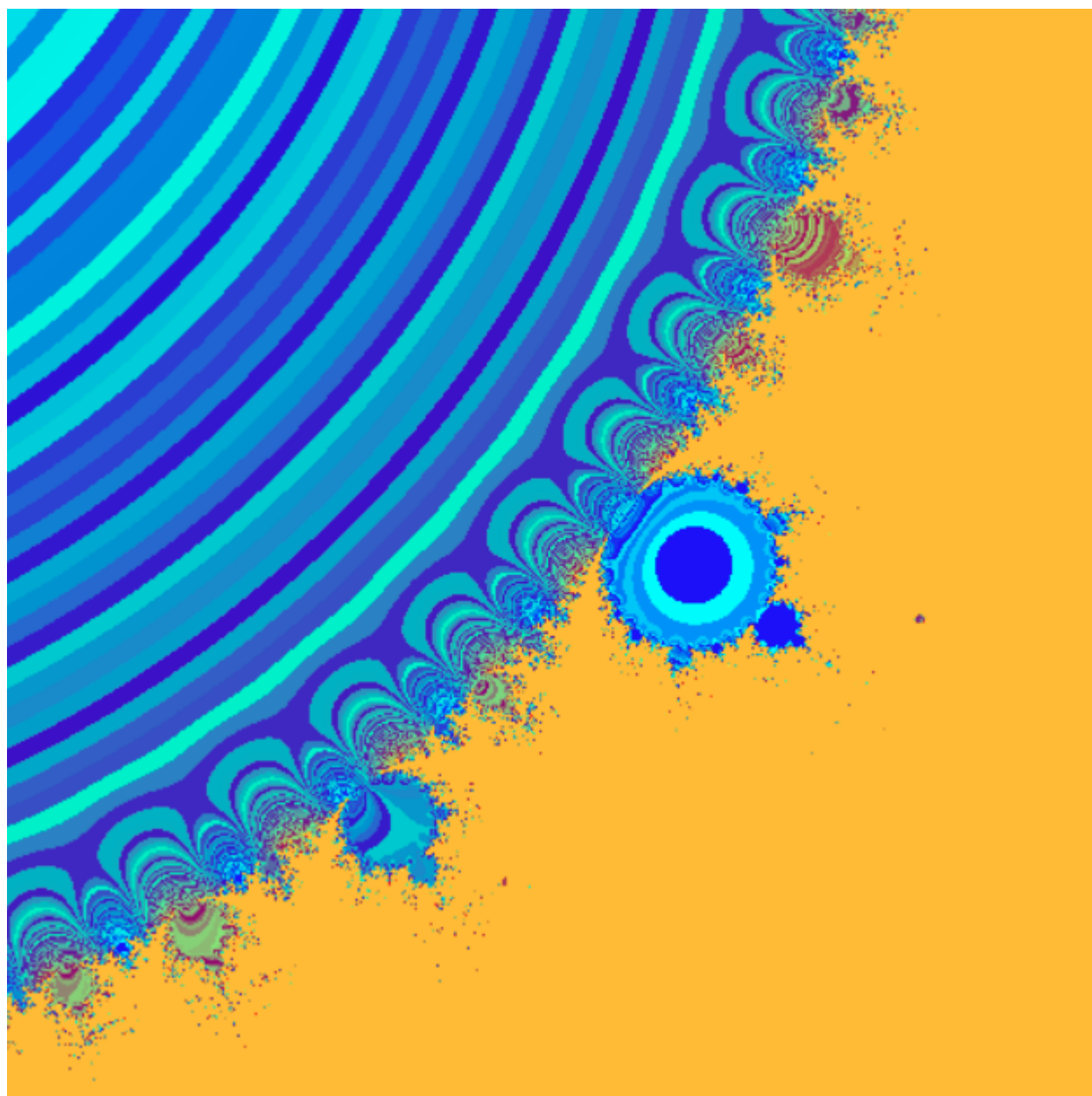
- 单核:



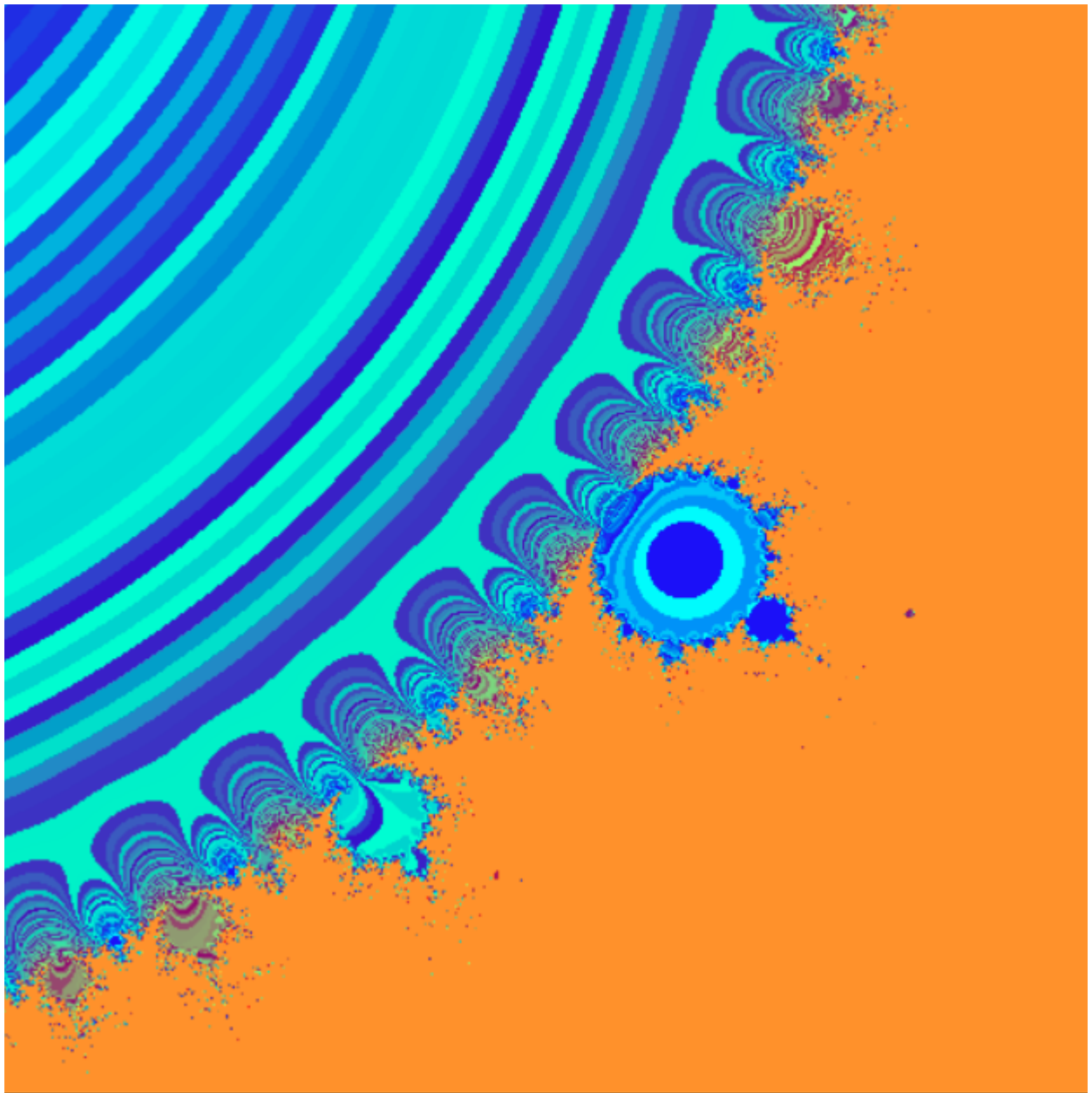
- 双核加速:



- 4核加速：



- 8核加速：



2.3 分析

可见在不同核加速状态下展示的图片颜色有所不同，这是因为图片的色谱与迭代次数相关，在不同核数的加速下迭代次数不同，所以不难理解颜色的变化。

3. Random Reduction

- 读懂并将串行算法Reduction.cpp改成mpi并行。
- 用Random_matrix.py生成随机矩阵。
- 用Validationg_mpi.cpp验证结果。

3.1 代码设计及优化

主要思想是设置一个长度为3的数组存储三个矩阵的计算值，由主进程收集子进程的计算信息再进行迭代：

```

/* Reductions with MPI */
double values[3]; // for storing matrices mul temp results
for (int i = 0; i < M; i++) {
    for (int j = 0; j < M; j++) {
        alpha = 0.0;
        beta = 0.0;
        gamma = 0.0;
        for (int k = 0; k < N; k++) {
            values[0] = U_t[i][k] * U_t[i][k];
            values[1] = U_t[j][k] * U_t[j][k];
            values[2] = U_t[i][k] * U_t[j][k];
            if (id != 0) {
                MPI_Send(values, 3, MPI_DOUBLE, 0, 1, MPI_COMM_WORLD);
            } else {
                for (int id = 1; id < nproc; id++) {
                    MPI_Recv(values, 3, MPI_DOUBLE, id, 1,
                        MPI_COMM_WORLD, &status);
                    alpha += values[0];
                    beta += values[1];
                    gamma += values[2];
                }
            }
        }
        // Global variables
        Alphas[i][j] = alpha;
        Betas[i][j] = beta;
        Gammas[i][j] = gamma;
    }
}

```

3.2 运行结果

运行：在终端该文件夹运行 `make`。

- 对200 * 200的矩阵进行 **Random Reduction**：


```
[*] Constructing symmetric matrix with size 200 * 200...
python Random_matrix.py 200 200
[*] Performing original reduction...
g++ Reduction.cpp -o Reduction && ./Reduction 200 200 -t -d
Time: 58.525 ms.

[*] Random reduction with MPI...
mpic++ randomRedMPI.cpp -o randomRedMPI && mpirun -np 2 ./randomRedMPI 200 200 -t -d
Time elapsed: 4019.89 ms

[*] Validating...
g++ Validation_mpi.cpp -o Validation_mpi && ./Validation_mpi -p
VALID!

difference in Alphas: 0
difference in Betas: 0
difference in Gammas: 0
```

3.3 分析

通过使用MPI库，通过并行计算加速，同时保证的三个目标矩阵的 `difference` 都为0，充分说明了并行计算的可靠性。

4. MPI IO

用MPI编写一个并行I/O的例子。

4.1 代码设计及优化

- 创建一维数组并在n个进程均匀分布（无法整除部分分配给编号末尾的进程），数组内容初始化为随机整数

```
/* Allocate buffer to procceses */
if (id != nproc-1)
    blocksize = bufsize/nproc;
else
    blocksize = bufsize-(nproc-1)*(bufsize/nproc);
block = (char*)malloc((blocksize+1)*sizeof(char));

/* Fill blocks with random integers */
srand(time(NULL));
for (int i = 0; i < blocksize; i++) {
    block[i] = (rand() % 10) + 1;
}
block[blocksize] = '\0';
```

- 利用并行I/O接口把数据写入文件中，输出每个进程写入的 `offset`

```

/* make sure all writes finish before we seek/read */
MPI_Barrier(comm);
MPI_File_open(comm, "mpiio.dat",
               MPI_MODE_CREATE | MPI_MODE_WRONLY,
               MPI_INFO_NULL, &fh);

offset = id*(bufsize/nproc);
cout<<"Offset of process "<<id<<" : "<<offset<<endl;

/* write to file due to process's offset */
MPI_File_write_at(fh, offset, block, blocksize, MPI_CHAR, &status);

```

- 执行一个集合操作，把所有进程的分块数据发送给0号进程，0号进程另外开一个1维数组空间a用户保存这些收取的数据

```

/* 0 process store data sent from slave processes in array A */
MPI_Barrier(comm);
if (id == 0) {
    A = (char*)malloc((bufsize+1)*sizeof(char));
    B = (char*)malloc((bufsize+1)*sizeof(char));

    /* copy 0's data to A */
    memcpy(A, block, blocksize);

    /* Recieve data from slaves' process and store in A */
    for (int i = 1; i < nproc; i++)
        if (i != nproc-1) {
            // must specify offset in A to store different processes'
data
            MPI_Recv(&A[i*(bufsize/nproc)], bufsize/nproc,
                    MPI_CHAR, i, 0, comm, &status);
            cout<<"Process "<<id<<" is recieving data from "<<i<<"..."
<<endl;
        } else {
            MPI_Recv(&A[(nproc-1)*(bufsize/nproc)], bufsize-
(bufsize/nproc)*(nproc-1),
                    MPI_CHAR, i, 0, comm, &status);
            cout<<"Process "<<id<<" is recieving data from "<<i<<"..."
<<endl;
        }

        cout<<"Process "<<id<<" revieced Done!"<<endl;
        free(block);
    } else {
        cout<<"Process "<<id<<" sending..."<<endl;
        MPI_Send(block, blocksize, MPI_CHAR, 0, 0, comm);
        free(block);
    }
}

```

- 0号进程另起一个串行I/O读入并行I/O操作写入文件的数据, 0号进程串行读入的输入放在1维数组空间b中, 对比a和b验证I/O和通信是否正确

```

    if (id == 0) {
        /* 0 process sequential read slave processes' I/O data into array B
*/
        B = fileWrite("mpiio.dat", B, bufsize);

        if (P == "-p") {
            cout<<"A: "<<endl;
            for (int i = 0; i < bufsize; i++)
                cout<<int(A[i])<<' ';
            cout<<'\n';

            cout<<"B: "<<endl;
            for (int i = 0; i < bufsize; i++)
                cout<<int(B[i])<<' ';
            cout<<'\n';
        }

        /* Validation */
        if (resultValidate(A, B, bufsize))
            cout<<"PASS"<<endl;
        else cout<<"FAIL"<<endl;

        free(A);
        free(B);
    }
}

```

4.2 运行结果

运行：在终端该文件夹运行 `make` 。

- 5核40个数据并行IO：

```

Shane > ... > testcases > parallel > parallelIO > mpirun --oversubscribe -np 5 MPIIO 40 -p
Process 0: 2 6 6 8 7 3 6 4
Process 2: 2 6 6 8 7 3 6 4
Process 3: 2 6 6 8 7 3 6 4
Process 4: 2 6 6 8 7 3 6 4
Process 1: 2 6 6 8 7 3 6 4
Offset of process 2 : 16
Offset of process 4 : 32
Offset of process 0 : 0
Offset of process 1 : 8
Offset of process 3 : 24
Process 1 sending...
Process 2 sending...
Process 3 sending...
Process 4 sending...
Process 0 is recieving data from 1...
Process 0 is recieving data from 2...
Process 0 is recieving data from 3...
Process 0 is recieving data from 4...
Process 0 revieced Done!
Writing files...
A:
2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4
B:
2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4 2 6 6 8 7 3 6 4
Validating results...
PASS

```

- 8核1000个数据并行IO:

```

Performing MPI IO using 8 cores...
mpic++ MPIIO.cpp -o MPIIO
mpirun --oversubscribe -np 8 MPIIO 1000
Offset of process 4 : 500
Offset of process 6 : 750
Offset of process 1 : 125
Offset of process 2 : 250
Offset of process 3 : 375
Offset of process 5 : 625
Offset of process 7 : 875
Offset of process 0 : 0
Process 5 sending...
Process 1 sending...
Process 2 sending...
Process 4 sending...
Process 6 sending...
Process 3 sending...
Process 7 sending...
Process 0 is recieving data from 1...
Process 0 is recieving data from 2...
Process 0 is recieving data from 3...
Process 0 is recieving data from 4...
Process 0 is recieving data from 5...
Process 0 is recieving data from 6...
Process 0 is recieving data from 7...
Process 0 revieced Done!
Writing files...
Validating results...
PASS

```

4.3 分析

通过对A和B的对比可以知道I/O没有出错，可以使用 "-p" 来输出进程通讯的信息来debug，从两个例子中可以看出通讯过程没有出现错误，结果符合预期。

总结

通过这学期对并行计算课程的学习，我受益匪浅，收获颇丰。深度理解了并行计算的基本原理，并且通过去无锡的参观，了解到并行计算技术在工业界的应用进展。此次的四个任务也让我充分地了解了并行计算编程的细节，学习并使用了并行计算库MPI和OpenMP解决和优化算法。

在后深度学习时代，并行计算无疑是充分利用好计算力的一把利剑，在今后的学习和实践中，我也应当将并行计算的优势发挥到其中。

References

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