

# High Performance Computing - Programming Paradigms and Scalability

## Exercise Sheet 5: Loop Dependencies, OpenMP

### 1 Loop Dependencies

Given is the following code fragment inside two nested loops:

```
1   for(int i = 3; i <= N; i++) {  
2       for(int j = 1; j <= M; j++) {  
3           A[i-3][j] = 2 * B[i][j+2];  
4           C[i][j]   = D[i, j+1] + A[i][j];  
5           B[i][j-1] = C[i][j];  
6       }  
7   }
```

- Examine these statements and name all occurring dependencies (flow dependence, anti-dependence, output dependence)! Input dependencies may be neglected.
- State for each dependency both distance and direction vector in order to check if it is a *loop-carried* or a *loop-independent* dependency.
- Could the two nested loops be (partially) run in parallel? Justify your answer!

## 2 Parallel Computation of $\pi$

With

$$\phi(x) = \frac{1}{1+x^2} \quad \text{and} \quad \int \phi(x)dx = \arctan(x)$$

one can compute  $\pi$  via the integration of  $\phi(x)$  over  $[0, 1]$ . The following code fragment shows how to compute  $\pi$  sequentially, subdividing the unit interval into  $N$  stripes.

```
1  int    i, N;
2  double h, x, sum, PI;
3
4  h = 1/N;
5  sum = 0.0;
6
7  for(i = 1 ; i <= N ; i++) {
8      x = h * (i - 0.5);
9      sum += 4.0 / (1.0 + x*x);
10 }
11
12 PI = h * sum;
```

Extend the program with valid OpenMP directives to compute  $\pi$  in parallel and think about sufficient synchronisation of the threads!

## 3 Parallel min-max-Search

To find the minimal and maximal elements `min` and `max`, resp., of a 3-dimensional integer array  $A$  of size  $3 \times 1000 \times 1000$ , the following sequential code is used:

```
1  int    i, j, k, min, max;
2
3  min = A[1][1][1];
4  max = A[1][1][1];
5
6  for(i=1; i <= 3; i++) {
7      for(j=1; j <= 1000; j++ ) {
8          for(k=1; k <= 1000; k++) {
9              if(A[i][j][k] < min) {
10                 min = A[i][j][k];
11             }
12             if(A[i][j][k] > max) {
13                 max = A[i][j][k];
14             }
15         }
16     }
17 }
```

Extend the program with valid OpenMP directives for the parallelisation of **one** loop and – if necessary – think about sufficient synchronisation of the threads!