Master Course – High-Performance Computing

Parallel Programming with OpenMP
Part II

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Outline — Data environment and combined constructs

- Introduction into OpenMP
- Programming and Execution Model
  - Parallel regions: team of threads
  - Syntax
  - Data environment (part 1)
  - Environment variables
  - Runtime library routines
  - Exercise 1: Parallel region / library calls / privat & shared variables
- Worksharing directives
  - Which thread executes which statement or operation?
  - Synchronization constructs, e.g., critical section
  - Exercise 2: Pi
- **Data environment and combined constructs**
  - **Nesting and Binding**
  - **Private and shared variables, Reduction clause**
  - **Combined parallel worksharing directives**
  - **Exercise 3: Pi with reduction clause and combined constructs**
  - **Exercise 4: Heat**
- Summary of OpenMP API
- OpenMP Pitfalls & Optimization Problems

Scope of variables (1)

```
#pragma omp parallel for \
 default(none) private(i)\
 shared (a,b,c)
 for (i=0; i<N; i++)
   a[i]=b[i]+c[i];
```

- Local variables of a method/function called in a parallel region are put onto the stack. They are **private**.
- Static variables of a function called in a parallel region are **shared**.
- The shared memory programming model:
  By default all variables are **shared**.
- Global variables (variables with a static or extern attribute) are **shared**.
- An exception are loop iteration variables, which automatically are **private.**
- The default can be changed by:
  default (shared|none).

Scope of variables (2)

- One can selectively change storage attributes constructs using the following clauses
  - **SHARED**
  - **PRIVATE**
  - **FIRSTPRIVATE**

- The default status can be modified with:
  - **DEFAULT (SHARED | NONE)**

- The value of a private variable inside a parallel loop can be transmitted to a global value outside the loop with:
  - **LASTPRIVATE**

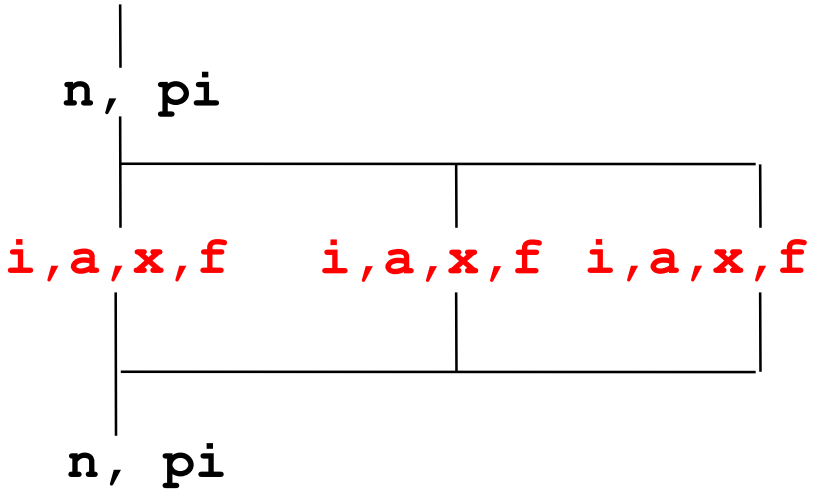
Scope of variables (3) - defaults

```
int n;
void calc_pi(double *);
main()
{
 double pi;
 ...
 #pragma omp parallel
 {
  for ( . . . )
  {
     call calc_pi( &pi )
  }
 } //end of parallel region
 ...
} // end of program main
```

```
extern int n;
void calc_pi(double *pi)
{
    int i;
    static double sum, h;
    double a, x, f;
    . . .
    *pi =
     ...
}
```

= shared

= private



n and pi are shared by all threads.

a, i, x, f are local to each thread

Scope of variables (4) - private

- **private(var)** creates a local copy of var for each thread.
  - The value is uninitialized
  - Private copy is *not* storage associated with the original

```
#include <stdio.h>
#include <omp.h>
int main(void)
{
  int i=42;
  printf("before PR: i=%d \n", i);
  #pragma omp parallel private(i)
  {
    printf("(%d):i=\n", omp_get_thread_num(), i);
    i+= omp_get_thread_num();
    printf("(%d):  i=%d\n", omp_get_thread_num(),i);
  }
 printf("after PR: i=%d \n", i);
}
```

An uninitialized copy is allocated for each thread

```
Output:
before PR: i=42
(0): i=0
(1): i=3445
(0):    i=1
(1):    i=3446
after PR: i=42
```

Scope of variables (4) – firstprivate, lastprivate

```
int main(void)
{
  int i=42;
  printf("before PR: i=%d \n", i);
  #pragma omp parallel firstprivate(i)
  {
    printf("(%d):\n", omp_get_thread_num(),i );
    i+= omp_get_thread_num();
    printf("(%d): i %d\n", omp_get_thread_num(),i
 }
 printf("after PR: i=%d \n", i);
}
```

The private copy is initialized with the original value before the parallel region

```
Output:
before PR: i=42
(0): i:42
(1): i:42
(0):    i:42
(1):    i:43
after PR: i=42
```

```
#pragma omp parallel firstprivate(i) lastprivate (i)
{
    printf("(%d):\n",omp_get_thread_num(),i );
    i+= omp_get_thread_num();
    printf("(%d): i %d\n",omp_get_thread_num(),i );
 }
```

i gets the value of the last (sequential) iteration

```
after PR: i=43
```

Scope of variables (5) - A data environment test

- Here's an example of **`private`** and **`firstprivate`**

```
variables A=1, B=1, and C=1
#pragma omp parallel private(B) shared(A) \
firstprivate(C)
```

- Inside the parallel region ...
  - "A" is shared by all threads; equals 1
  - "B" and "C" are local to each thread.
    - B's initial value is undefined
    - C's initial value equals 1
- Outside this parallel region ...
  - The values of "B" and "C" are undefined.

Critical regions (6) − Reduction clause

```
for(i=0;i<100;i++)
   s= s + a[i];
```

```
#pragma omp parallel for \
 private(i) reduction(+:s)
 for (i=0; i<100; i++)
    s += a[i];
```

The reduction clause is tailored for this frequently occurring case

`reduction({op}:list})`

with

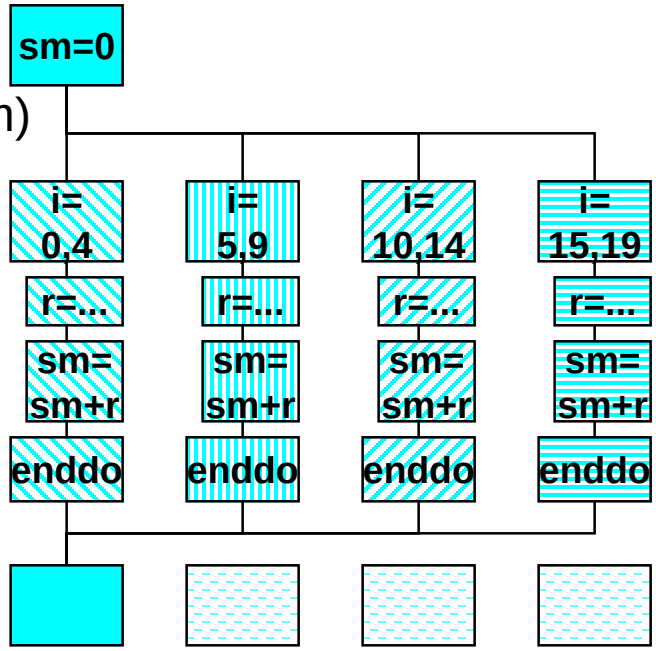
`op = { + | * | - | || | && }`

list is a comma separated list of variables.

OpenMP reduction — an example (C/C++)

C / C++:

```
      sm = 0;
#pragma omp parallel for reduction(+:sm)
      for( i=0; i<20; i++)
      {   double r;
          r = work(i);
          sm = sm + r ;
      } /*end for*/
/*omp end parallel for*/
```



Outline — Exercise 3: pi with reduction

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  - **Exercise 3: Pi with reduction clause and combined constructs**
  - **Exercise 4: Heat (Assignment 1)**

In-class exercise 3: pi Program (1)

- Goal: usage of
  - worksharing constructs: **`do/for`**
  - **`critical directive`**
  - **`reduction clause`**
  - combined parallel worksharing constructs: **`parallel do/parallel for`**
  - Modify **pi2.c** -> **pi3.c**
- remove **`critical`** directive in **pi.3c**, add **`reduction`** clause and compile
- set environment variable **`OMP_NUM_THREADS`** to **`2`** and run
  - value of pi?
- run again
  - value of pi?
- set environment variable **`OMP_NUM_THREADS`** to **`4`** and run
  - value of pi? execution time?
- run again
  - value of pi? execution time?

In-class exercise 3: pi Program (2)

- change parallel region **`+ do/for`** to the combined parallel worksharing construct **`parallel for`** and compile
- set environment variable **`OMP_NUM_THREADS`** to **`2`** and run
  - value of pi?
- run again
  - value of pi?
- set environment variable **`OMP_NUM_THREADS`** to **`4`** and run
  - value of pi?
- run again
  - value of pi?
- At the end, compile again **without** OpenMP
  - Does your code still compute a **correct** value of **pi?**

OpenMP Bugs – Example 1

```
25    a[0] = 0;
26    #pragma omp parallel for
27    for (i=1; i<N; i++)
28    {
29       a[i] = 2.0*i*(i-1);
30       b[i] = a[i] – a[i-1];
31    } // end of omp parallel for
```

- What´s wrong?

- How to solve?

OpenMP Bugs– Analysis 1

ID	Short Info	Type	Con-text	Description	1st Access	2. Access
1	Write ->Read	Error	omp for	Memory **read** of **a[]** at "test.c:**30** conflicts with a prior memory **write** of **a[]** at test.c: **29** (flow dependencies)	"test.c": 29	"test.c": 30

```
25    a[0] = 0;
26    #pragma omp parallel for
27    for (i=1; i<N; i++)
28    {
29       a[i] = 2.0*i*(i-1);
30       b[i] = a[i] - a[i-1];
31    } // end of omp parallel for
```

Solution:

- Two separate loops → will cause bad cache reuse! **or**
- Re-computing of a[i-1] i.e. b[i] = a[i] – 2.0*(i-1)*(i-2);

OpenMP Bugs – Example 2

```
43   a[0] = 0;
44   #pragma omp parallel
45   {
46     #pragma omp for nowait
47     for (i=1; i<N; i++)
48     {
49       a[i] = 3.0*i*(i+1)
50     } // end of omp for nowait
51     #pragma omp for
52     for (i=1; i<N; i++)
53     {
54       b[i] = a[i] – a[i-1];
55     } // end of omp for
56   } // end of omp parallel
```

- What´s wrong?

- How to solve?

OpenMP Bugs – Analysis 2

ID	Short Info	Type	Con-text	Description	1st Access	2. Access
2	Write ->Read Data-race	Error	omp par-allel region	Memory **read** of **a[]** at "test.c:**54** conflicts with a prior memory **write** of **a[]** at test.c: **49** (flow dependencies)	"test.c": **49**	"test.c": **54**
3	Read ->Write	Error	omp par-allel region	Memory **write** of **a[]** at "test.c:**49** conflicts with a prior memory **read** of **a[]** at test.c: **54** (anti dependencies)	"test.c": **54**	"test.c": **49**

```
43 a[0] = 0;
44 #pragma omp parallel
45 {
46  #pragma omp for nowait
47  for (i=1; i<N; i++)
48  {
49   a[i] = 3.0*i*(i+1)
50  } // end of omp for nowait
```

```
51  #pragma omp for
1    for (i=1; i<N; i++
2    {
54        b[i] = a[i] - a[i-1];
1    } // end of omp for
56} // end of omp parallel
```

Solution: Remove nowait

OpenMP Bugs – Example 3

```
68   #pragma omp parallel for
69    for (i=1; i<N; i++)
70    {
71       x = sqrt(b[i]) - 1;
72       a[i] = x*x + 2*x + 1
73     } // end of omp parallel for
```

- What´s wrong?

- How to solve?

OpenMP Bugs – Analysis 3

ID	Short Info	Type	Con-text	Description	1st Access	2. Access
4	Write ->Write Datarace	Error	omp for	Memory write of **x** at "test.c:**71** conflicts with a prior memory **write** of **x** at test.c: **71** (output dependencies)	"test.c": **71**	"test.c": **72**
5	Read ->Write	Error	omp for	Memory write of **x** at "test.c:**71** conflicts with a prior memory **read** of **x** at test.c: **72** (anti dependencies)	"test.c": **72**	"test.c": **71**

```
68    #pragma omp parallel for
69     for (i=1; i<N; i++)
70     {
71        x = sqrt(b[i]) - 1;
72        a[i] = x*x + 2*x + 1
73      } // end of omp parallel for
```

Solution: Add privat(x)

In the printed version, the solutions can be found in the appendix

OpenMP Bugs – Example 4

```
84     f = 2;
85   # pragma omp parallel for private (f,x)
86     for (i=1; i<N; i++)
87     {
88        x = f * b[i];
89        a[i] = x - 7;
90     } // end of omp parallel for
91     a[0] = x;
```

- What´s wrong?

- How to solve?

OpenMP Bugs – Analysis 4

ID	Short Info	Type	Con-text	Description	1st Access	2. Access
6	undefined in access	Caution	omp parallel region	OpenMP – the access at "test.c":88 is undefined, the expected value was defined at "test.c":84 in serial execut.	"test.c": 84	"test.c": 88
7	undefined in access	Warning	"test.c": 17	OpenMP – undefined in the serial code (original program) at "test.c":91 with "test.c": 88	"test.c": 88	"test.c": 91

```
84     f = 2;
85   # pragma omp parallel for private (f,x)
86     for (i=1; i<N; i++)
87     {
88        x = f * b[i];
89        a[i] = x - 7;
90     } // end of omp parallel for
91     a[0] = x;
```

Solution: Use firstprivate(f) lastprivate(x) instead of private(f,x)

OpenMP Bugs – Example 5

```
101     sum = 0;
102   # pragma omp parallel
103     for (i=1; i<N; i++)
104     {
105        sum = sum + b[i];
107     } // end of omp parallel for
```

- What´s wrong?

- How to solve?

OpenMP Bugs – Analysis 5

ID	Short Info	Type	Con-text	Description	1st Access	2. Access
8	Read ->Write	Error	omp for	Memory **write** of sum at "test.c:**105** conflicts with a prior memory **read** of **sum** at test.c: **105** (anti dependencies)	"test.c": **105**	"test.c": **105**

```
101     sum = 0;
102   # pragma omp parallel for
103     for (i=1; i<N; i++)
104     {
105        sum = sum + b[i];
107     } // end of omp parallel for
```

Solution: Add reduction(+:sum)

In the printed version, the solutions can be found in the appendix

Appendix

Example 1:

- Two separate loops → will cause bad cache reuse! **or**
- Re-computing of a[i-1] i.e. b[i] = a[i] – 2.0*(i-1)*(i-2);

Example 2:

- Remove nowait

Example 3:

- Add privat(x)

Example 4:

- Use firstprivate(f) lastprivate(x) instead of private(f,x)

Example 5:

- Add reduction(+:sum)