A “Hands-on” Introduction to OpenMP*

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Data environment:
Default storage attributes

- Shared Memory programming model:
  - Most variables are shared by default
- Global variables are SHARED among threads
  - Fortran: COMMON blocks, SAVE variables, MODULE variables
  - C: File scope variables, static
  - Both: dynamically allocated memory (ALLOCATE, malloc, new)
- But not everything is shared...
  - Stack variables in subprograms(Fortran) or functions(C) called from parallel regions are PRIVATE
  - Automatic variables within a statement block are PRIVATE.

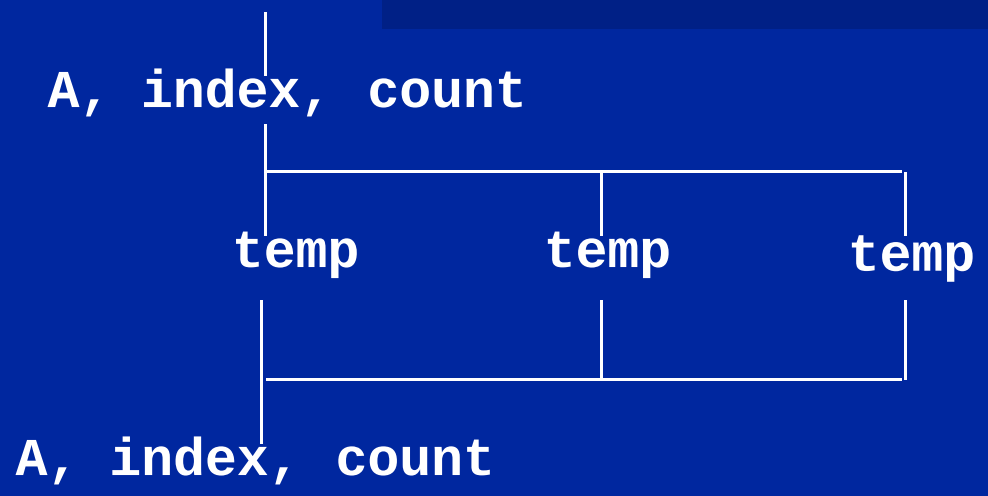
Data sharing: Examples

```
double A[10];
int main() {
int index[10];
#pragma omp parallel
      work(index);
printf("%d\n", index[0]);;
}
```

```
extern double A[10];
void work(int *index) {
  double temp[10];
  static int count;
  ...
}
```

A, index and count are shared by all threads.

temp is local to each thread



Data sharing:
Changing storage attributes

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

All the clauses on this page apply to the OpenMP construct NOT to the entire region.

- The final value of a private inside a parallel loop can be transmitted to the shared variable outside the loop with:
  - LASTPRIVATE
- The default attributes can be overridden with:
  - DEFAULT (PRIVATE | SHARED | NONE)

    DEFAULT(PRIVATE) *is Fortran only*

*All data clauses apply to parallel constructs and worksharing constructs except "shared" which only applies to parallel constructs.

Data Sharing: Private Clause

- **private(var) creates a new local copy of var for each thread.**
  - **The value of the private copies is uninitialized**
  - **The value of the original variable is unchanged after the region**

```
void wrong() {
    int tmp = 0;
#pragma omp parallel for private(tmp)
    for (int j = 0; j < 1000; ++j)
            tmp += j;
    printf("%d\n", tmp);
}
```

tmp was not initialized

tmp is 0 here

Data Sharing: Private Clause When is the original variable valid?

- The original variable's value is unspecified if it is referenced outside of the construct
  - Implementations may reference the original variable or a copy ….. a dangerous programming practice!
  - For example, consider what would happen if the compiler inlined work()?

```
int tmp;
void danger() {
      tmp = 0;
#pragma omp parallel private(tmp)
      work();
     printf("%d\n", tmp);;
}
```

tmp has unspecified value

```
extern int tmp;
void work() {
      tmp = 5;
}
```

unspecified which copy of tmp

Firstprivate Clause

- Variables initialized from shared variable
- C++ objects are copy-constructed

```
incr = 0;
#pragma omp parallel for firstprivate(incr)
for (i = 0; i <= MAX; i++) {
        if ((i%2)==0) incr++;
        A[i] = incr;
}
```

Each thread gets its own copy of incr with an initial value of 0

Lastprivate Clause

- Variables update shared variable using value from last iteration
- C++ objects are updated as if by assignment

```
void sq2(int n, double *lastterm)
{
    double x; int i;
    #pragma omp parallel for lastprivate(x)
    for (i = 0; i < n; i++){
        x = a[i]*a[i] + b[i]*b[i];
        b[i] = sqrt(x);
    }
    *lastterm = x;
}
```

"x" has the value it held for the "last sequential" iteration (i.e., for i=(n-1))

Data Sharing:
A data environment test

- Consider this example of PRIVATE and FIRSTPRIVATE

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

- Are A,B,C local to each thread or shared inside the parallel region?
- What are their initial values inside and values after the parallel region?

Inside this 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

Following the parallel region ...

- B and C revert to their original values of 1
- A is either 1 or the value it was set to inside the parallel region

Data Sharing: Default Clause

- Note that the default storage attribute is DEFAULT(SHARED) (so no need to use it)
  - Exception: #pragma omp task
- To change default: DEFAULT(PRIVATE)
  - *each* variable in the construct is made private as if specified in a private clause
  - mostly saves typing
- DEFAULT(NONE): *no* default for variables in static extent. Must list storage attribute for each variable in static extent. Good programming practice!

Only the Fortran API supports default(private).

C/C++ only has default(shared) or default(none).

The Mandelbrot Area program

```
#include <omp.h>
# define NPOINTS 1000
# define MXITR 1000
void testpoint(void);
struct d_complex{
   double r;     double i;
};
struct d_complex c;
int numoutside = 0;

int main(){
   int i, j;
   double area, error, eps  = 1.0e-5;
#pragma omp parallel for default(shared) private(c,eps)
   for (i=0; i<NPOINTS; i++) {
     for (j=0; j<NPOINTS; j++) {
       c.r = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
       c.i = 1.125*(double)(j)/(double)(NPOINTS)+eps;
       testpoint();
     }
   }
area=2.0*2.5*1.125*(double)(NPOINTS*NPOINTS-
numoutside)/(double)(NPOINTS*NPOINTS);
   error=area/(double)NPOINTS;
}
```

```
void testpoint(void){
struct d_complex z;
      int iter;
      double temp;

      z=c;
      for (iter=0; iter<MXITR; iter++){
        temp = (z.r*z.r)-(z.i*z.i)+c.r;
        z.i = z.r*z.i*2+c.i;
        z.r = temp;
        if ((z.r*z.r+z.i*z.i)>4.0) {
          numoutside++;
          break;
        }
      }
}
```

When I run this program, I get a different incorrect answer each time I run it … there is a race condition!!!!

Debugging parallel programs

- Find tools that work with your environment and learn to use them. A good parallel debugger can make a huge difference.
- But parallel debuggers are not portable and you will assuredly need to debug "by hand" at some point.
- There are tricks to help you. The most important is to use the default(none) pragma

```
#pragma omp parallel for default(none) private(c,  eps)
  for (i=0; i<NPOINTS; i++) {
    for (j=0; j<NPOINTS; j++) {
      c.r = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
      c.i = 1.125*(double)(j)/(double)(NPOINTS)+eps;
      testpoint();
    }
  }
}
```

Using default(none) generates a compiler error that j is unspecified.

The Mandelbrot Area program

```
#include <omp.h>
# define NPOINTS 1000
# define MXITR 1000
struct d_complex{
   double r;     double i;
};
void testpoint(struct d_complex);
struct d_complex c;
int numoutside = 0;

int main(){
   int i, j;
   double area, error, eps  = 1.0e-5;
#pragma omp parallel for default(shared) private(c, j) \
    firstprivate(eps)
   for (i=0; i<NPOINTS; i++) {
     for (j=0; j<NPOINTS; j++) {
       c.r = -2.0+2.5*(double)(i)/(double)(NPOINTS)+eps;
       c.i = 1.125*(double)(j)/(double)(NPOINTS)+eps;
       testpoint(c);
     }
   }
area=2.0*2.5*1.125*(double)(NPOINTS*NPOINTS-
numoutside)/(double)(NPOINTS*NPOINTS);
   error=area/(double)NPOINTS;
```

```
void testpoint(struct  d_complex  c){
struct d_complex z;
      int iter;
      double temp;

      z=c;
      for (iter=0; iter<MXITR; iter++){
        temp = (z.r*z.r)-(z.i*z.i)+c.r;
        z.i = z.r*z.i*2+c.i;
        z.r = temp;
        if ((z.r*z.r+z.i*z.i)>4.0) {
        #pragma omp atomic
          numoutside++;
          break;
        }
      }
}
```

Other errors found using a debugger or by inspection:

- **eps was not initialized**
- **Protect updates of numoutside**
- **Which value of c did testpoint() see? Global or private?**

Serial PI Program

Now that you understand how to modify the data environment, let's take one last look at our pi program.

```
static long num_steps = 100000;
double step;
int main ()
{           int i;   double x, pi, sum = 0.0;

            step = 1.0/(double) num_steps;

            for (i=0;i< num_steps; i++){
                        x = (i+0.5)*step;
                        sum = sum + 4.0/(1.0+x*x);
            }
            pi = step * sum;
}
```

What is the minimum change I can make to this code to parallelize it?

Example: Pi program … minimal changes

```
#include <omp.h>
static long num_steps = 100000;        double step;

void main ()
{          int i;    double x, pi, sum = 0.0;
           step = 1.0/(double) num_steps;
#pragma omp parallel for private(x) reduction(+:sum)
           for (i=0;i< num_steps; i++){
                      x = (i+0.5)*step;
                      sum = sum + 4.0/(1.0+x*x);
           }
           pi = step * sum;
}
```

For good OpenMP implementations, reduction is more scalable than critical.

i private by default

Note: we created a parallel program without changing any executable code and by adding 2 simple lines of text!