PRACE TRAINING COURSE under PRACE Advance Training Centre at BSC

BSC-CNS http://www.bsc.es/
PRACE project http://www.prace-ri.eu/
PRACE Training Portal http://www.training.prace-ri.eu/
PATC @ BSC Training Program
http://www.bsc.es/marenostrum-support-services/hpc-trainings/prace-trainings

Session 5: Parallel Programming with OpenMP

Xavier Martorell

Barcelona Supercomputing Center

Agenda

10:00 - 11:00	OpenMP fundamentals, parallel regions
11:00 - 11:30	Worksharing constructs
11:30 - 12:00	Break
12:00 - 12:15	Synchronization mechanisms in OpenMP
12:15 - 13:00	Practical: heat diffusion
13:00 - 14:00	Lunch
14:00 - 14:30	Tasking in OpenMP
14:30 - 15:30	Programming using a hybrid MPI/OpenMP approach
15:30 - 16:00	Break
16:00 - 17:00	Practical: heat diffusion

Part I

OpenMP fundamentals, parallel regions

Outline

- OpenMP Overview
- The OpenMP model
- Writing OpenMP programs
- Creating Threads
- Data-sharing attributes

Outline

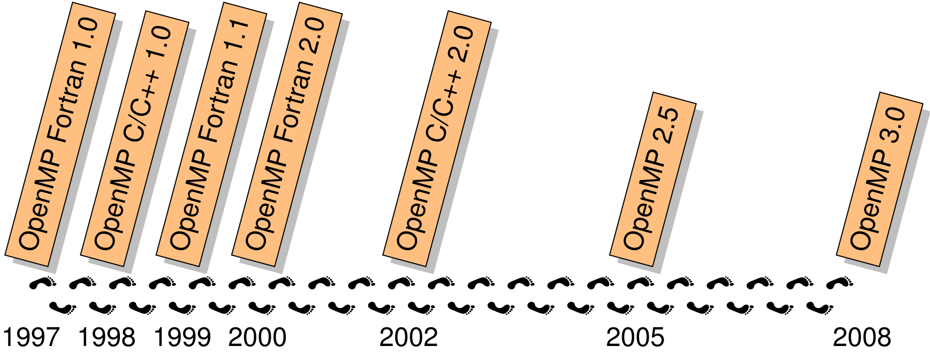
- OpenMP Overview
- The OpenMP model
- Writing OpenMP programs
- Creating Threads
- Data-sharing attributes

What is OpenMP?

- It's an API extension to the C, C++ and Fortran languages to write parallel programs for shared memory machines
  - Current version is 3.0 (May 2008)
  - Supported by most compiler vendors
    - Intel,IBM,PGI,Sun,Cray,Fujitsu,HP,GCC,...
- Maintained by the Architecture Review Board (ARB), a consortium of industry and academia

http://www.openmp.org

A bit of history



Advantages of OpenMP

- Mature standard and implementations
  - Standardizes practice of the last 20 years
- Good performance and scalability
- Portable across architectures
- Incremental parallelization
- Maintains sequential version
- (mostly) High level language
  - Some people may say a medium level language :-)
- Supports both task and data parallelism
- Communication is implicit

Disadvantages of OpenMP

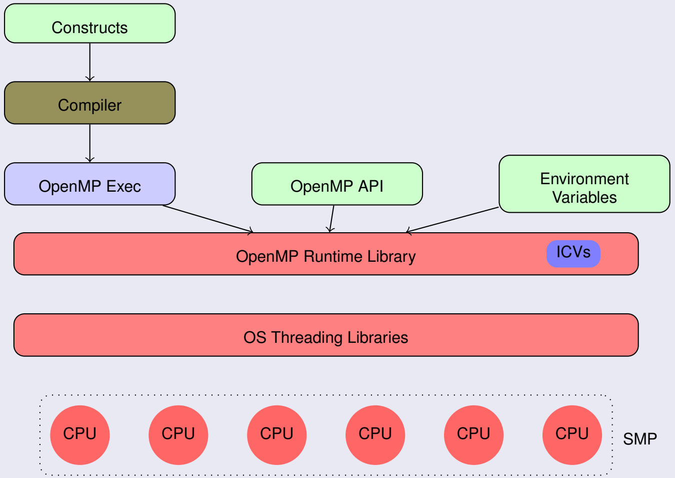
- Communication is implicit
- Flat memory model
- Incremental parallelization creates false sense of glory/failure
- No support for accelerators
- No error recovery capabilities
- Difficult to compose
- Lacks high-level algorithms and structures
- Does not run on clusters

Outline

- OpenMP Overview
- The OpenMP model
- Writing OpenMP programs
- Creating Threads
- Data-sharing attributes

OpenMP at a glance

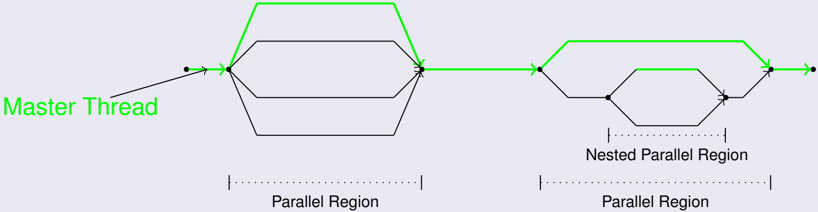
OpenMP components



Execution model

Fork-join model

- OpenMP uses a fork-join model
  - The master thread spawns a team of threads that joins at the end of the parallel region
  - Threads in the same team can collaborate to do work



Memory model

- OpenMP defines a relaxed memory model
  - Threads can see different values for the same variable
  - Memory consistency is only guaranteed at specific points
  - Luckily, the default points are usually enough
- Variables can be shared or private to each thread

Outline

OpenMP directives syntax

In Fortran

Through a specially formatted comment:

```
sentinel construct [clauses]
```

where sentinel is one of:

- `!$OMP` or `C$OMP` or `*$OMP` in fixed format
- `!$OMP` in free format

In C/C++

Through a compiler directive:

```
#pragma omp construct [clauses]
```

- OpenMP syntax is ignored if the compiler does not recognize OpenMP

OpenMP directives syntax

In Fortran

Through a specially formatted comment:

```
sentinel construct [clauses]
```

where sentinel is one of:

- `!$OMP` or `C$OMP` or `*$OMP` in fixed format
- `!$OMP` in free format

In C/C++

Through a compiler directive:

```
#pragma omp construct [clauses]
```

- OpenMP syntax is ignored if the compiler does not recognize

We'll be using C/C++ syntax through this tutorial

Headers/Macros

C/C++ only

- omp.h contains the API prototypes and data types definitions
- The _OPENMP is defined by OpenMP enabled compiler
  - Allows conditional compilation of OpenMP

Fortran only

- The omp_lib module contains the subroutine and function definitions

Structured Block

Definition

Most directives apply to a structured block:

- Block of one or more statements
- One entry point, one exit point
  - No branching in or out allowed
- Terminating the program is allowed

Outline

- OpenMP Overview
- The OpenMP model
- Writing OpenMP programs
- Creating Threads
- Data-sharing attributes

The parallel construct

Directive

```
#pragma omp parallel [clauses]
    structured block
```

where clauses can be:

- **num_threads(*expression*)**
- **if(*expression*)**
- shared(*var-list*) ← Coming shortly!
- private(*var-list*) ← Coming shortly!
- firstprivate(*var-list*) ← Coming shortly!
- default(none|shared| private | firstprivate) ← Coming shortly! / Only in Fortran
- reduction(*var-list*) ← We'll see it later
- copyin(*var-list*) ← Not today

The parallel construct

Specifying the number of threads

- The number of threads is controlled by an internal control variable (**ICV**) called **nthreads-var**.
- When a parallel construct is found a parallel region with a maximum of **nthreads-var** is created
  - Parallel constructs can be nested creating nested parallelism
- The **nthreads-var** can be modified through
  - the **omp_set_num_threads** API called
  - the **OMP_NUM_THREADS** environment variable
- Additionally, the **num_threads** clause causes the implementation to ignore the ICV and use the value of the clause for that region.

The parallel construct

Avoiding parallel regions

- Sometimes we only want to run in parallel under certain conditions
  - E.g., enough input data, not running already in parallel, ...
- The **`if`** clause allows to specify an *expression*. When evaluates to false the **`parallel`** construct will only use 1 thread
  - Note that still creates a new team and data environment

Putting it together

Example

```
void main () {
  #pragma omp parallel
     ...
  omp_set_num_threads(2);
  #pragma omp parallel
     ...
  #pragma omp parallel num_threads(random()%4+1) if(0)
     ...
}
```

Putting it together

Example

```
void main () {
  #pragma omp parallel
    ...
  omp_set_num_threads(2);
  #pragma omp parallel
    ...
  #pragma omp parallel num_threads(random()%4+1) if(0)
    ...
}
```

An unknown number of threads here. Use **OMP_NUM_THREADS**

Putting it together

Example

```
void main () {
  #pragma omp parallel
    ...
  omp_set_num_threads(2);
  #pragma omp parallel
    ...  ← A team of two threads here.
  #pragma omp parallel num_threads(random()%4+1) if(0)
    ...
}
```

Putting it together

Example

```
void main () {
  #pragma omp parallel
     ...
  omp_set_num_threads(2);
  #pragma omp parallel
     ...
  #pragma omp parallel num_threads(random()%4+1) if(0)
     ...
}
```

A team of 1 thread here.

API calls

Other useful routines

int **omp_get_num_threads**()	Returns the number of threads in the current team
int **omp_get_thread_num**()	Returns the id of the thread in the current team
int **omp_get_num_procs**()	Returns the number of processors in the machine
int **omp_get_max_threads**()	Returns the maximum number of threads that will be used in the next parallel region
double **omp_get_wtime**()	Returns the number of seconds since an arbitrary point in the past

Outline

- OpenMP Overview
- The OpenMP model
- Writing OpenMP programs
- Creating Threads
- Data-sharing attributes

Data environment

A number of clauses are related to building the data environment that the construct will use when executing.

- **`shared`**
- **`private`**
- **`firstprivate`**
- **`default`**
- **`threadprivate`**
- lastprivate
- reduction
- copyin
- copyprivate

We'll see them later

Out of our scope today

Data-sharing attributes

Shared

When a variable is marked as **`shared`**, the variable inside the construct is the same as the one outside the construct.

- In a parallel construct this means all threads see the same variable
  - but not necessarily the same value
- Usually need some kind of synchronization to update them correctly
  - OpenMP has consistency points at synchronizations

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel shared(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel shared(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

Prints 2 or 3

Data-sharing attributes

Private

When a variable is marked as **`private`**, the variable inside the construct is a new variable of the same type with an undefined value.

- In a parallel construct this means all threads have a different variable
- Can be accessed without any kind of synchronization

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel private(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel private(x) num_threads(2)
{
   x++;
   printf("%d\n",x);   <- Can print anything
}
printf("%d\n",x);
```

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel private(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

Prints 1

Data-sharing attributes

Firstprivate

When a variable is marked as `firstprivate`, the variable inside the construct is a new variable of the same type but it is initialized to the original variable value.

- In a parallel construct this means all threads have a different variable with the same initial value
- Can be accessed without any kind of synchronization

Data-sharing attributes

Example

```c
int x=1;
#pragma omp parallel firstprivate(x) num_threads(2)
{
   x++;
   printf("%d\n",x);
}
printf("%d\n",x);
```

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel firstprivate(x) num_threads(2)
{
    x++;
    printf("%d\n",x);  ←  Prints 2 (twice)
}
printf("%d\n",x);
```

Data-sharing attributes

Example

```
int x=1;
#pragma omp parallel firstprivate(x) num_threads(2)
{
    x++;
    printf("%d\n",x);
}
printf("%d\n",x);
```

Prints 1

Data-sharing attributes

What is the default?

- Static/global storage is **`shared`**
- Heap-allocated storage is **`shared`**
- Stack-allocated storage inside the construct is **`private`**
- Others
  - If there is a **`default`** clause, what the clause says
    - **`none`** means that the compiler will issue an error if the attribute is not explicitly set by the programmer
  - Otherwise, depends on the construct
    - For the **`parallel`** region the default is **`shared`**

Data-sharing attributes

Example

```
int x,y;
#pragma omp parallel private(y)
{
    x =
    y =
    #pragma omp parallel private(x)
    {
        x =
        y =
    }
}
```

Data-sharing attributes

Example

```
int x,y;
#pragma omp parallel private(y)
{
    x =
    y =
    #pragma om
    {
        x =
        y =
    }
}
```

x is **shared**

y is **private**

ivate(x)

Data-sharing attributes

Example

```
int x,y;
#pragma omp parallel private(y)
{
    x =
    y =
    #pragma omp parallel private(x)
    {
        x =     x is private
        y =     y is shared
    }
}
```

Threadprivate storage

The threadprivate construct

```
#pragma omp threadprivate(var-list)
```

- Can be applied to:
  - Global variables
  - Static variables
  - Class-static members
- Allows to create a per-thread copy of “global” variables.
- **threadprivate** storage persist across **parallel** regions if the number of threads is the same

Threadprivate persistence across nested regions is complex

Threaprivate storage

Example

```
char* foo ()
{
  static char buffer[BUF_SIZE];
  #pragma omp threadprivate(buffer)

  ...

  return buffer;
}
```

Threaprivate storage

Example

```
char* foo ()
{
  static char buffer[BUF_SIZE];
  #pragma omp threadprivate(buffer)

  ...

  return buffer;
}
```

Creates one *static* copy of *buffer* per thread

Threaprivate storage

Example

```
char* foo ()
{
  static char buffer[BUF_SIZE];
  #pragma omp threadprivate(buffer)

  ...

  return buffer;
}
```

Now foo can be called by multiple threads at the same time

Part II

Worksharing constructs

Outline

- The worksharing concept
- Loop worksharing

Outline

- The worksharing concept
- Loop worksharing

Worksharings

Worksharing constructs divide the execution of a code region among the threads of a team

- Threads cooperate to do some work
- Better way to split work than using thread-ids
- Lower overhead than using **`tasks`**
  - But, less flexible

In OpenMP, there are four worksharing constructs:

- single
- loop worksharing
- section
- workshare

We'll see them later

Restriction: worksharings cannot be nested

Outline

- The worksharing concept
- Loop worksharing

Loop parallelism

The for construct

```
#pragma omp for [clauses]
    for( init-expr ; test-expr ; inc-expr )
```

where clauses can be:

- private
- firstprivate
- **lastprivate(*variable-list*)**
- **reduction(*operator:variable-list*)**
- **schedule(*schedule-kind*)**
- **nowait**
- **collapse(*n*)**
- ordered

We'll see it later

The for construct

How it works?

The iterations of the loop(s) associated to the construct are divided among the threads of the team.

- Loop iterations must be independent
- Loops must follow a form that allows to compute the number of iterations
- Valid data types for inductions variables are: integer types, pointers and random access iterators (in C++)
  - The induction variable(s) are automatically privatized
- The default data-sharing attribute is **`shared`**

It can be merged with the **`parallel`** construct:

```
#pragma omp parallel for
```

The for construct

Example

```
void foo (int *m, int N, int M)
{
  int i;
  #pragma omp parallel for private(j)
  for ( i = 0; i < N; i++ )
     for ( j = 0; j < M; j++ )
        m[i][j] = 0;
}
```

The for construct

Example

```
void foo (int *m, int N, int M)
{
  int i;
  #pragma omp parallel for priva
  for ( i = 0; i < N; i++ )
     for ( j = 0; j < M; j++ )
        m[i][j] = 0;
}
```

New created threads cooperate to execute all the iterations of the loop

The for construct

Example

```
void foo (int *m, int N, int M)
{
  int i;
  #pragma omp parallel for private(i)
  for ( i = 0;
    for ( j = 0; j < M; j++ )
      m[i][j] = 0;
}
```

The *i* variable is automatically privatized

The for construct

Example

```
void foo (int *m, int N, int M)
{
  int i;
  #pragma omp parallel for private(j)
  for ( i = 0; i < N; i++ )
     for ( j = 0;
        m[i][j] = 0;
}
```

Must be explicitly privatized

The for construct

Example

```
void foo ( std::vector<int> &v )
{
  #pragma omp parallel for
  for ( std::vector<int>::iterator it = v.begin() ;
        it < v.end() ;
        it ++ )
     *it = 0;
}
```

The for construct

Example

```
void foo ( std::vector<int> &v )
{
  #pragma omp parallel for
  for ( std::vector<int>::iterator it =
        it < v.end() ;
        it ++ )
     *it = 0;
}
```

random access iterators (and pointers) are valid types

The for construct

Example

```
void foo ( std::vector<int> &v )
{
  #pragma omp parallel for
  for ( std::vector<int>::iterator it = v.begin() ;
        it < v.end() ;
        it ++ )
     *it = 0;
}
```

!= cannot be used in the test expression

Removing dependences

Example

```
x = 0;
for ( i = 0; i < n; i++ )
{
    v[i] = x;
    x += dx;
}
```

Each iteration *x* depends on the previous one. Can't be parallelized

Removing dependences

Example

```
x = 0;
for ( i = 0; i < n; i++ )
{
    x = i * dx;
    v[i] = x;
}
```

But *x* can be rewritten in terms of *i*.
Now it can be parallelized

The lastprivate clause

When a variable is declared **`lastprivate`**, a private copy is generated for each thread. Then the value of the variable in the last iteration of the loop is copied back to the original variable.

- A variable can be both **`firstprivate`** and **`lastprivate`**

The reduction clause

A very common pattern is where all threads accumulate some values into a single variable

- E.g., n += v[i], our pi program, ...
- Using **`critical`** or **`atomic`** is not good enough
  - Besides being error prone and cumbersome

Instead we can use the **`reduction`** clause for basic types.

- Valid operators are: +,-,*,|,||,&,&&,^
- The compiler creates a **`private`** copy that is properly initialized
- At the end of the region, the compiler ensures that the **`shared`** variable is properly (and safely) updated.

We can also specify **`reduction`** variables in the **`parallel`** construct.

The reduction clause

Example

```
int vector_sum (int n, int v[n])
{
   int i, sum = 0;
   #pragma omp parallel for reduction(+:sum)
   {
      for ( i = 0; i < n; i++ )
         sum += v[i];
   }
   return sum;
}
```

The reduction clause

Example

```
int vector_sum (int n, int v[n])
{
   int i, sum = 0;
   #pragma omp parallel for reduction(+:sum)
   {
      for ( i = 0; i < n; i++ )
         sum += v[i];
   }
   return sum;
}
```

Private copy initialized here to the identity value

Shared variable updated here with the partial values of each thread

The schedule clause

The **schedule** clause determines which iterations are executed by each thread.

- If no **schedule** clause is present then is implementation defined

There are several possible options as schedule:

- **STATIC**
- **STATIC,chunk**
- **DYNAMIC[,chunk]**
- **GUIDED[,chunk]**
- **AUTO**
- **RUNTIME**

The schedule clause

Static schedule

The iteration space is broken in chunks of approximately size $N/num-threads$. Then these chunks are assigned to the threads in a Round-Robin fashion.

Static,N schedule (Interleaved)

The iteration space is broken in chunks of size N. Then these chunks are assigned to the threads in a Round-Robin fashion.

Characteristics of static schedules

- Low overhead
- Good locality (usually)
- Can have load imbalance problems

The schedule clause

Dynamic,N schedule

Threads dynamically grab chunks of N iterations until all iterations have been executed. If no chunk is specified, $N = 1$.

Guided,N schedule

Variant of **`dynamic`**. The size of the chunks deceases as the threads grab iterations, but it is at least of size N. If no chunk is specified, $N = 1$.

Characteristics of dynamic schedules

- Higher overhead
- Not very good locality (usually)
- Can solve imbalance problems

The schedule clause

Auto schedule

In this case, the implementation is allowed to do whatever it wishes.

- Do not expect much of it as of now

Runtime schedule

The decision is delayed until the program is run through the **sched-nvar** ICV. It can be set with:

- The **OMP_SCHEDULE** environment variable
- The **omp_set_schedule**() API call

The nowait clause

When a worksharing has a **`nowait`** clause then the implicit **`barrier`** at the end of the loop is removed.

- This allows to overlap the execution of non-dependent loops/tasks/worksharings

The nowait clause

Example

```
#pragma omp for nowait
for ( i = 0; i < n ; i++ )
   v[i] = 0;
#pragma omp for
for ( i = 0; i < n ; i++ )
   a[i] = 0;
```

First and second loop are independent so we can overlap them

The nowait clause

Example

```
#pragma omp for nowait
for ( i = 0; i < n ; i++ )
   v[i] = 0;
#pragma omp for
for ( i = 0; i < n ; i++ )
   a[i] = 0;
```

On a side note, you would be better by fusing the loops in this case

The nowait clause

Example

```
#pragma omp for nowait
for ( i = 0; i < n ; i++ )
    v[i] = 0;
#pragma omp for
for ( i = 0; i < n ; i++ )
    a[i] = v[i]*v[i];
```

First and second loop are dependent!. No guarantees that the previous iteration is finished

The nowait clause

Exception: static schedules

If the two (or more) loops have the same **static** schedule and all have the same number of iterations.

Example

```
#pragma omp for schedule(static,2) nowait
for ( i = 0; i < n ; i++ )
   v[i] = 0;
#pragma omp for schedule(static,2)
for ( i = 0; i < n ; i++ )
   a[i] = v[i]*v[i];
```

The collapse clause

Allows to distribute work from a set of *n* nested loops.

- Loops must be perfectly nested
- The nest must traverse a rectangular iteration space

The collapse clause

Allows to distribute work from a set of *n* nested loops.

- Loops must be perfectly nested
- The nest must traverse a rectangular iteration space

Example

```
#pragma omp for collapse(2)
for ( i = 0; i < N; i++ )
   for ( j = 0; j < M; j++ )
      foo (i,j);
```

i and *j* loops are folded and iterations distributed among all threads. Both *i* and *j* are privatized

Coffee time! :-)

Part III

Basic Synchronizations

Outline

- Thread barriers

- Exclusive access

Why synchronization?

Mechanisms

Threads need to synchronize to impose some ordering in the sequence of actions of the threads. OpenMP provides different synchronization mechanisms:

- **`barrier`**
- **`critical`**
- **`atomic`**
- taskwait
- ordered
- locks

We'll see them later

Outline

- Thread barriers

- Exclusive access

Thread Barrier

The barrier construct

#pragma `omp barrier`

- Threads cannot proceed past a barrier point until all threads reach the barrier AND all previously generated work is completed
- Some constructs have an implicit `barrier` at the end
    - E.g., the `parallel` construct

Barrier

Example

```
#pragma omp parallel
{
    foo();
#pragma omp barrier
    bar();
}
```

Barrier

Example

```
#pragma omp parallel
{
    foo ( ) ;
#pragma omp barrier
    bar ( ) ;
}
```

Forces all foo occurrences too happen before all bar occurrences

Barrier

Example

```
#pragma omp parallel
{
    foo();
#pragma omp barrier
    bar();
}
```

Implicit barrier at the end of the parallel region

Outline

- Thread barriers
- Exclusive access

Exclusive access

The critical construct

```
#pragma omp critical [(name)]
    structured block
```

- Provides a region of mutual exclusion where only one thread can be working at any given time.
- By default all critical regions are the same, but you can provide them with names
  - Only those with the same name synchronize

Critical construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp critical
    x++;
}
printf("%d\n",x);
```

Critical construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp critical
    x++;
}
printf("%d\n",x);
```

Only one thread at a time here

Critical construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp critical
     x++;
}
printf("%d\n",x);
```

Only one thread at a time here

Prints 3!

Critical construct

Example

```
int x=1,y=0;
#pragma omp parallel num_threads(4)
{
#pragma omp critical (x)
    x++;
#pragma omp critical (y)
    y++;
}
```

Critical construct

Example

```
int x=1,y=0;
#pragma omp parallel num_threads(4)
{
#pragma omp critical (x)
     x++;
#pragma omp critical (y)
     y++;
}
```

Different names: One thread can update *x* while another updates *y*

Exclusive access

The atomic construct

```
#pragma omp atomic
    expression
```

- Provides an special mechanism of mutual exclusion to do read & update operations
- Only supports simple read & update expressions
  - E.g., x += 1, x = x - foo()
- Only protects the read & update part
  - foo() not protected
- Usually much more efficient than a `critical` construct
- Not compatible with `critical`

Atomic construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp atomic
    x++;
}
printf("%d\n",x);
```

Atomic construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp atomic
    x++;
}
printf("%d\n",x);
```

Only one thread at a time updates *x* here

Atomic construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp atomic
    x++;
}
printf("%d\n",x);
```

Prints 3!

Atomic construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp critical
    x++;
#pragma omp atomic
    x++;
}
printf("%d\n",x);
```

Atomic construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp critical
     x++;
#pragma omp atomic
     x++;
}
printf("%d\n",x);
```

Different threads can update *x* at the same time!

Atomic construct

Example

```
int x=1;
#pragma omp parallel num_threads(2)
{
#pragma omp critical
    x++;
#pragma omp atomic
    x++;
}
printf("%d\n",x);
```

Prints 3,4 or 5 :(

Part IV

Practical: heat diffusion

Outline

- Heat diffusion

Outline

- Heat diffusion

Before you start

Enter the OpenMP directory to do the following exercises.

Description of the Heat Diffusion app Hands-on

Parallel loops

The file solver.c implements the computation of the Heat diffusion

1. Annotate the jacobi, redblack, and gauss functions with OpenMP
2. Execute the application with different numbers of processors, and compare the results

Bon appétit!*

*Disclaimer: actual food may differ from the image! :-)

Part V

Task Parallelism in OpenMP

Outline

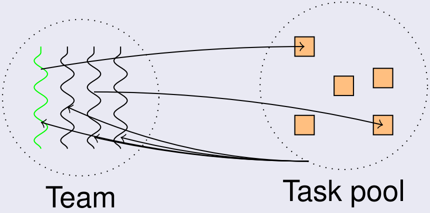
- OpenMP tasks
- Task synchronization
- The single construct
- Task clauses
- Common tasking problems

Outline

- OpenMP tasks
- Task synchronization
- The single construct
- Task clauses
- Common tasking problems

Task parallelism in OpenMP

Task parallelism model



- Parallelism is extracted from “several” pieces of code
- Allows to parallelize very unstructured parallelism
  - Unbounded loops, recursive functions, ...

What is a task in OpenMP ?

- Tasks are work units whose execution may be deferred
  - they can also be executed immediately
- Tasks are composed of:
  - code to execute
  - a data environment
    - Initialized at creation time
  - internal control variables (ICVs)
- Threads of the team cooperate to execute them

Creating tasks

The task construct

```
#pragma omp task [clauses]
    structured block
```

Where clauses can be:

- shared
- private
- firstprivate
    - Values are captured at creation time
- default
- **if(*expression*)**
- **untied**

When are task created?

- `Parallel` regions create tasks
  - One implicit task is created and assigned to each thread
    - So all task-concepts have sense inside the parallel region
- Each thread that encounters a `task` construct
  - Packages the code and data
  - Creates a new explicit task

Default task data-sharing attributes

When there are no clauses ...

If no default clause

- Implicit rules apply
  - e.g., global variables are shared
- Otherwise...
  - **`firstprivate`**
  - **`shared`** attribute is lexically inherited

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a =
            b =
            c =
            d =
            e =
}}}
```

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = shared
            b =
            c =
            d =
            e =
}}}
```

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = shared
            b = firstprivate
            c =
            d =
            e =
}}}
```

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = shared
            b = firstprivate
            c = shared
            d =
            e =
}}}
```

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = shared
            b = firstprivate
            c = shared
            d = firstprivate
            e =
}}}
```

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = shared
            b = firstprivate
            c = shared
            d = firstprivate
            e = private
}}}
```

Task default data-sharing attributes

In practice...

Example

```
int a;
void foo() {
  int b,c;
  #pragma omp parallel shared(b)
  #pragma omp parallel private(b)
  {
        int d;
        #pragma omp task
        {
            int e;

            a = shared
            b = firstprivate
            c = shared
            d = firstprivate
            e = private
}}}
```

Tip: `default(none)` is your friend if you do not see it clearly

List traversal

Example

```
void traverse_list ( List l )
{
  Element e;
  for ( e = l->first; e ; e = e->next )
     #pragma omp task
       process(e);
}
```

e is **firstprivate**

Outline

- OpenMP tasks
- Task synchronization
- The single construct
- Task clauses
- Common tasking problems

Task synchronization

There are two main constructs to synchronize tasks:

- `barrier`
  - Remember: all previous work (including tasks) must be completed
- `taskwait`

Waiting for children

The taskwait construct

```
#pragma omp taskwait
```

Suspends the current task until all children tasks are completed

- Just direct children, not descendants

Taskwait

Example

```
void traverse_list ( List l )
{
  Element e;
  for ( e = l->first; e ; e = e->next )
     #pragma omp task
       process(e);

  #pragma omp taskwait
}
```

All tasks guaranteed to be completed here

Taskwait

Example

```
void traverse_list ( List l )
{
  Element e;
  for ( e = l->first; e ; e = e->next )
     #pragma omp task
       process(e);

  #pragma omp taskwait

}
```

Now we need some threads to execute the tasks

List traversal

Completing the picture

Example

```
List l

#pragma omp parallel
    traverse_list(l);
```

List traversal

Completing the picture

Example

```
List l

#pragma omp parallel
    traverse_list(l);
```

This will generate multiple traversals

List traversal

Completing the picture

Example

```
List l

#pragma omp parallel
   traverse_list(l);
```

We need a way to have a single thread execute traverse_list

Outline

Giving work to just one thread

The single construct

```
#pragma omp single [clauses]
   structured block
```

- where clauses can be:
  - private
  - firstprivate
  - nowait ← We'll see it later
  - copyprivate ← Not today
- Only one thread of the team executes the structured block
- There is an implicit **barrier** at the end

The single construct

Example

```
int main (int argc, char **argv )
{
    #pragma omp parallel
    {
       #pragma omp single
       {
          printf("Hello␣world!\n");
       }
    }
}
```

The single construct

Example

```
int main (int argc, char **argv )
{
    #pragma omp parallel
    {
       #pragma omp single
       {
           printf("Hello world!\n");
       }
    }
}
```

This program outputs just one “Hello world”

List traversal

Completing the picture

Example

```
List l

#pragma omp parallel
#pragma single
   traverse_list(l);
```

List traversal

Completing the picture

Example

```
List l

#pragma omp parallel
#pragma single
   traverse_list(l);
```

One thread creates the tasks of the traversal

List traversal

Completing the picture

Example

```
List l

#pragma omp parallel
#pragma single
    traverse_list(l);
```

All threads cooperate to execute them

Outline

- OpenMP tasks
- Task synchronization
- The single construct
- **Task clauses**
- Common tasking problems

Task scheduling

How it works?

Tasks are tied by default

- Tied tasks are executed always by the same thread
  - Not necessarily the creator
- Tied tasks have scheduling restrictions
  - Deterministic scheduling points (creation, synchronization, ...)
    - Tasks can be suspended/resumed at these points
  - Another constraint to avoid deadlock problems
- Tied tasks may run into performance problems

The untied clause

A task that has been marked as **`untied`** has none of the previous scheduling restrictions:

- Can *potentially* switch to any thread
- Can *potentially* switch at any moment
- Bad mix with thread based features
  - thread-id, critical regions, threadprivate
- Gives the runtime more flexibility to schedule tasks

The if clause

- If the the expression of an **`if`** clause evaluates to false
  - The encountering task is suspended
  - The new task is executed immediately
    - with its own data environment
    - different task with respect to synchronization
  - The parent task resumes when the task finishes
  - Allows implementations to optimize task creation
    - For very fine grain task you may need to do your own if

Outline

- OpenMP tasks
- Task synchronization
- The single construct
- Task clauses
- Common tasking problems

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution*/
    for (i = 0; i < n; i++)

    {
       state[j] = i;
       if (ok(j+1,state)) {
         search(n,j+1,state);
       }
    }
}
```

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution*/
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       state[j] = i;
       if (ok(j+1,state)) {
         search(n,j+1,state);
       }
    }
}
```

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       state[j] = i;
       if (ok(j+1,state)) {
         search(n,j+1,state);
       }
    }
}
```

Data scoping

Because it's an orphaned task all variables are firstprivate

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       state[j] = i;
       if (ok(j+1,state)) {
         search(n,j+1,state);
       }
    }
}
```

Data scoping

Because it's an orphaned task all variables are firstprivate

State is not captured

Just the pointer is captured not the pointed data

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       state[j] = i;
       if (ok(j+1,state)) {
         search(n,j+1,state);
       }
    }
}
```

Problem #1

Incorrectly capturing pointed data

Problem #1

Incorrectly capturing pointed data

Problem

firstprivate does not allow to capture data through pointers

Solutions

1. Capture it manually
2. Copy it to an array and capture the array with firstprivate

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution*/
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state,state,sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)) {
         search(n,j+1,new_state);
       }
    }
}
```

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution*/
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state, state, sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)) {
         search(n,j+1,new_state);
       }
    }
}
```

Caution!

Will new_state still be valid by the time memcpy is executed?

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state, state, sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)) {
         search(n,j+1,new_state);
       }
    }
}
```

Problem #2

Data can go out of scope!

Problem #2

Out-of-scope data

Problem

Stack-allocated parent data can become invalid before being used by child tasks

- Only if not captured with firstprivate

Solutions

1. Use firstprivate when possible
2. Allocate it in the heap
   - Not always easy (we also need to free it)
3. Put additional synchronizations
   - May reduce the available parallelism

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state,state,sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)) {
         search(n,j+1,new_state);
       }
    }

    #pragma omp taskwait
}
```

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state, state, sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)) {
         search(n,j+1,new_state);
       }
    }

    #pragma omp taskwait
}
```

Shared variable needs protected access

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      solutions++;
      return;
    }

    /* try each possible solution */
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state,state,sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)) {
         search(n,j+1,new_state);
       }
    }

    #pragma omp taskwait
}
```

Solutions

- Use **critical**
- Use **atomic**
- Use **threadprivate**

Reductions for tasks

Example

```
int solutions=0;
int mysolutions=0;
#pragma omp threadprivate(mysolutions)

void start_search ()
{
  #pragma omp parallel
  {
     #pragma omp single
     {
         bool initial_state[n];
         search(n,0,initial_state);
     }
     #pragma omp atomic
         solutions += mysolutions;
  }

}
```

Use a separate counter for each thread

Accumulate them at the end

Search problem

Example

```
void search (int n, int j, bool *state)
{
    int i,res;

    if (n == j) {
      /* good solution, count it */
      mysolutions++;
      return;
    }

    /* try each possible solution*/
    for (i = 0; i < n; i++)
    #pragma omp task
    {
       bool *new_state = alloca(sizeof(bool)*n);
       memcpy(new_state,state,sizeof(bool)*n);
       new_state[j] = i;
       if (ok(j+1,new_state)){
         search(n,j+1,new_state);
       }
    }

    #pragma omp taskwait
}
```

Part VI

Programming using a hybrid MPI/OpenMP approach

Outline

- MPI+OpenMP programming

Outline

- MPI+OpenMP programming

Alternatives

MPI + computational kernels in OpenMP

Use OpenMP directives to exploit parallelism between communication phases

- OpenMP parallel will end before new communication calls

MPI inside OpenMP constructs

Call MPI from within for-loops, or tasks

- MPI needs to support multi-threaded mode

Compiling MPI+OpenMP

MPI compiler driver gets the proper OpenMP option

- mpicc -openmp
- mpicc -fopenmp

Coffee time! :-)

Part VII

Practical: heat diffusion

Outline

- MPI+OpenMP Heat diffusion

Outline

- MPI+OpenMP Heat diffusion

Before you start

Enter the MPI+OpenMP directory to do the following exercises.

Description of the Heat Diffusion app Hands-on

Parallel loops

The file solver.c implements the computation of the Heat diffusion.

1. Use MPI to distribute the work across nodes
2. Annotate the jacobi, redblack, and gauss functions with OpenMP tasks
3. Execute the application with different numbers of nodes/processors, and compare the results