Multi-Core Programming with OpenMP

Outline:

- Multi-core computer architecture (brief)
- OpenMP — the Basics
- Lunch Break
- OpenMP — the Advanced Story

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Exploiting Loop-Level Parallelism with OpenMP

So far: Limited to individual loops:

- No relationship between subsequent parallelizable loops.
- Parallel execution environment repeatedly set up and terminated.
- Frequent barrier synchronizations
- Limited scope for optimization

Wanted: Larger parallel sections

- Containing several parallel loops
- Containing other work sharing constructs
- Barrier synchronization only as necessary
- Overlapping of different parallel activities

Example: Mandelbrot with Dithering

Sequential code:

```
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
  }
}

for (i=0; i<M; i++) {
  for (j=1; j<N-1; j++) {
    dith[i,j] = 0.5 * depth[i,j]
              + 0.25 * depth[i,j-1]
              + 0.25 * depth[i,j+1];
  }
}
```

Outline:

1. Compute Mandelbrot picture
2. Perform dithering step

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Mandelbrot with Dithering

Loop-parallelized code:

```
#pragma omp parallel for private(i,j,x,y)
for (i=0; i<M; i++) {
  for (j=0; j<N; j++) {
    x = (double) i / (double) M;
    y = (double) j / (double) N;
    depth[i,j] = mandelval( x, y, max);
  }
}

#pragma omp parallel for private(i,j)
for (i=0; i<M; i++) {
  for (j=1; j<N-1; j++) {
    dith[i,j] = 0.5 * depth[i,j]
              + 0.25 * depth[i,j-1]
              + 0.25 * depth[i,j+1];
  }
}
```

Disadvantage:

- Between the two parallel loops:
  - All threads hit synchronization barrier.
  - Worker threads are terminated.
  - Worker threads are re-created.
- **Avoidable overhead !!**
- Way out: Decoupling of
  - parallelization
  - work sharing

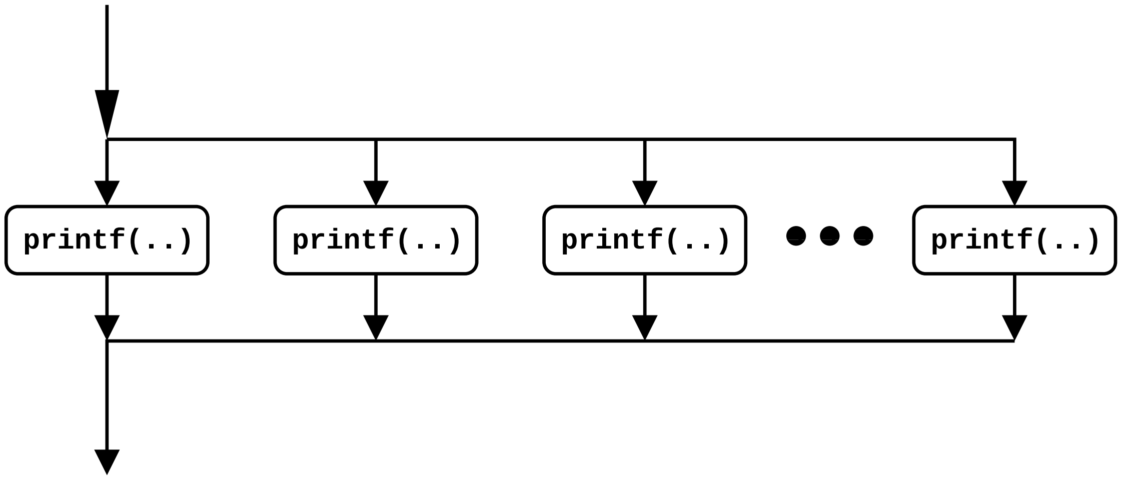
Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

SPMD-Style Parallel Regions

Introducing the `parallel`-directive:

```
#pragma omp parallel
{
  printf( "Hello world says thread %d.\n", omp_get_thread_num());
}
```

Effect:



SPMD-Style Parallel Regions

Introducing the `parallel`-directive:

```
#pragma omp parallel
{
  ...
}
```

Meaning:

- The entire code block following the `parallel`-directive is executed by **all** threads concurrently.
- This includes:
  - creation of worker threads,
  - SPMD-style code execution,
  - barrier synchronization,
  - termination of worker threads.

SPMD-Style Parallel Regions

Introducing the `parallel`-directive:

```
#pragma omp parallel
{
  ...
}
```

Available clauses:

- `private` (*list of variables*)
- `firstprivate` (*list of variables*)
- `shared` (*list of variables*)
- `reduction` (*operator* : *list of variables*)
- `if` (*logical expression*)

All clauses behave exactly as with `parallel for` directive.

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Work Sharing in Parallel Regions

Problem:

- All threads execute identical code within parallel region.
- It is not very useful to let them do exactly the same.
- Work needs to be explicitly shared among threads.

Divide work based on thread number:

```
#pragma omp parallel private( whoami, nthreads)
{
  nthreads = omp_get_num_threads();
  whoami   = omp_get_thread_num();

  do_the_work( whoami, nthreads);
}
```


Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Work Sharing Constructs in OpenMP

Loop scheduling with the `for`-directive:

```
int i;
...
#pragma omp parallel private(i)
{

  #pragma omp for

  for (i=0; i<N; i++) {
    array[i] = ... ;
  }
}
```

⟺

```
int i;
...

#pragma omp parallel for

for (i=0; i<N; i++) {
  array[i] = ... ;
}
```

- Work sharing / loop scheduling done implicitly by OpenMP
- Directive `parallel for` is equivalent to nested separate directives `parallel` and `for`
- Caution: Loop variables needs explicit privatization

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Parallelism vs Work Sharing

The `parallel` directive:

- defines a parallel region
- starts team of worker threads
- performs a synchronization barrier
- terminates team of worker threads

The `for` directive:

- does **not** start / stop any threads
- distributes loop iterations among (already running) threads
- **within** a parallel region
- performs a synchronization barrier

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Again: Mandelbrot with Dithering

Region-parallelized code:

```
#pragma omp parallel private(i,j,x,y)
{
  #pragma omp for
  for (i=0; i<M; i++) {
    for (j=0; j<N; j++) {
      x = (double) i / (double) M;
      y = (double) j / (double) N;
      depth[i,j] = mandelval( x, y, max);
  } }

  #pragma omp for
  for (i=0; i<M; i++) {
    for (j=1; j<N-1; j++) {
      dith[i,j] = 0.5 * depth[i,j]
                + 0.25 * depth[i,j-1]
                + 0.25 * depth[i,j+1];
  } }
}
```

Advantages:

- Larger parallel region
- Less thread termination/recreation overhead
- Less communication overhead
- Opportunity for further optimization...

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Again: Mandelbrot with Dithering

Region-parallelized code:

```
#pragma omp parallel private(i,j,x,y)
{
  #pragma omp for nowait schedule(static)
  for (i=0; i<M; i++) {
    for (j=0; j<N; j++) {
      x = (double) i / (double) M;
      y = (double) j / (double) N;
      depth[i,j] = mandelval( x, y, max);
  } }

  #pragma omp for nowait schedule(static)
  for (i=0; i<M; i++) {
    for (j=1; j<N-1; j++) {
      dith[i,j] = 0.5 * depth[i,j]
                + 0.25 * depth[i,j-1]
                + 0.25 * depth[i,j+1];
  } }
}
```

New clause: `nowait`:

- Effect: no synchronization barrier after work sharing construct

Advantages:

- Avoid unnecessary synchronization overhead
- After first parallel loop:
  No need to wait for any other thread to finish due to restricted data dependence
- After second parallel loop:
  Synchronization done by parallel section anyways

Non-Loop Work Sharing: Parallel Sections

Example:

```
#pragma omp parallel
{
  ...
  #pragma omp sections
  {
    #pragma omp section
    {  ...
    }
    #pragma omp section
    {  ...
    }
    ...
  }
  ...
}
```

How it works:

- Each parallel section is executed by exactly one thread.
- Threads execute different (maybe unrelated) code
- Mapping of threads to sections is done implicitly.
- #threads $>$ #sections :
  Some threads do nothing.
- #threads $<$ #sections :
  Some threads do multiple sections.
- Synchronization barrier completes `sections` directive.
- The `parallel` directive and the `sections` directive can be combined into the `parallel sections` directive (in analogy to the `parallel for` directive).

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Parallel Sections

Clauses of `sections` directive:

- `private (`*`list of variables`*`)`
  - private copy
  - not initialized from surrounding context
- `firstprivate (`*`list of variables`*`)`
  - private copy
  - initialized with pre-section value
- `lastprivate (`*`list of variables`*`)`
  - private copy
  - value in last section propagated outside
- `reduction (`*`operator`*` : `*`list of variables`*`)`
  - private copy
  - each section's value folded with reduction operator and result propagated outside

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Parallel Sections Example

Simulation Program:

- Read input data from file.
- Perform three independent preprocessing steps:
  1. Interpolation of input data to regular grid.
  2. Gathering statistics about input data.
  3. Generation of random parameters for Monte Carlo simulation.
- Perform simulation.

```
data = read_input( );
#pragma omp parallel sections
{
  #pragma omp section
  {
    grid = interpolate( data);
  }
  #pragma omp section
  {
    stats = compute_statistics( data);
  }
  #pragma omp section
  {
    rands = generate_rand_params( );
  }
}
simulate( grid);
```


Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Assigning Work to a Single Thread

The `single` directive:

- Work sharing construct
- Exactly one thread executes code block
- Synchronization barrier afterwards
- Useful to “interrupt” parallel region
- `nowait` clause leaves out synchronization
- Semantically equivalent but usually more efficient than two separate parallel regions

```
#pragma omp parallel \
        shared( in, out, len, array)
{
  ...
  #pragma omp single
  {
    read_array( in, array, len);
  }
  #pragma omp for
  for (i=0; i<len; i++) {
    array[i] = fun( array[i]);
  }
  #pragma omp single nowait
  {
    write_array( out, array, len);
  }
  ...
}
```


Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Work Sharing Constructs in OpenMP

Restrictions:

- Single point of entry.
  - No jumps into work sharing construct.
- Single point of exit.
  - No jumps out of work sharing construct.
  - No `return` or `break` statements.
- All threads must encounter work sharing construct in same order.
  - No subsets of thread teams.
- No nesting
  - Control reaches work sharing construct while already executing another one:
    - Programming error.
    - Behaviour undefined.

Orphaned Work Sharing Constructs

What is that ?

- Work sharing construct outside lexical scope of surrounding parallel region.
- Perfectly fine with OpenMP.
- Work sharing construct is associated with innermost parallel region in dynamic function call tree.

No parallel region around ?

- If work sharing construct is encounterd during serial execution, it behaves like when executed by a team of a single thread.

Example:

```
void work( )
{ ...
  #pragma omp parallel
  {
    initialize( array, N);
  } ...
}

void initialize( int *a, int N)
{
  int i;
  #pragma omp for
  for (i=0; i<N; i++) {
    array[i] = ... ;
  }
}
```

Thread Private Global Variables

Idea:

- Global variables are always shared between all threads.
- Sometimes, it is more convenient to have individual copy for each thread.
- Analogy to *thread specific data (TSD)* in PThreads.
- Thread private instances of global variables survive across different parallel regions.
- Conceptually, there are N+1 instances, one for the master thread and one for each worker thread.

Example:

```
#pragma omp threadprivate
int my_id;

int main()
{
  #pragma omp parallel
  {
    my_id = omp_get_thread_num();
    ...
  }
  ...
}
```


Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Thread Private Global Variables

The `copyin` clause:

- Usually, there is no way to exchange data stored in thread private variables between threads.
- The `copyin` clause allows to initialize all copies with master thread's value when entering parallel region.

Example:

```
#pragma omp threadprivate
int N, my_id;

int main()
{
  N = ... ;

  #pragma omp parallel copyin (N)
  {
    my_id = omp_get_thread_num();
    ...
    N = fun( N, my_id);
  }
  ...
}
```

Synchronization Barrier in OpenMP

The `barrier` directive:

- All threads wait at barrier until last thread reaches barrier.
- Allows for explicit control over synchronization barriers independent of work sharing constructs.

Example:

```
#pragma omp parallel
{
    ...
  #pragma omp barrier
    ...
}
```


Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

Low-level Synchronization

Similar API as PThreads:

```
void omp_init_lock( omp_lock_t *lock);
void omp_destroy_lock(omp_lock_t *lock);
void omp_set_lock(omp_lock_t *lock);
void omp_unset_lock(omp_lock_t *lock);
int omp_test_lock(omp_lock_t *lock);
```

Nested critical sections:

- Same problems as with mutex locks in PThreads.
- May deadlock easily.
- OpenMP provides no specific means for deadlock prevention or detection.

Conclusion

Advantages:

- Simpler to use than other concepts, for example PThreads.
- OpenMP implementation responsible for most organizational aspects.
- Simplicity facilitates experimentation with alternatives, e.g. scheduling techniques.
- Large applications may be parallelized incrementally.

Disadvantages:

- Simplicity reduces programmers' reflections on parallelism.
- Insight into impact of certain directives / clauses is reduced.
- False directives may lead to wrong — even non-deterministic — behaviour.
- False directives are easy to write but hard to find.
- Performance considerations lead to low-level "expert" code.

Outlook: OpenMP 3.0

Extensions:

- Nested parallel regions:
  - Parallel regions may be nested lexically or dynamically
  - Additional level of parallelism
  - New team of threads started
  - Creator thread becomes master of that new team
  - Controlled by `num_threads` clause
- Independent tasks:
  - Spawn concurrent evaluation of some expression
  - Wait on termination of spawned tasks
  - Clauses control visibility of variables
- ...

OpenMP Research

Research projects:

- OpenMP for the Cell
- OpenMP for GPGPUs
- Extension for OpenMP for GPGPUs
- ...

Dr. Clemens Grelck
Computer Systems Architecture
University of Amsterdam

The End

Questions ?

More information:

www.openmp.org