Shared Memory Parallelism - OpenMP

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Credits/Sources:

OpenMP C/C++ standard (openmp.org)

OpenMP tutorial (http://www.llnl.gov/computing/tutorials/openMP/#Introduction)

OpenMP sc99 tutorial presentation (openmp.org)

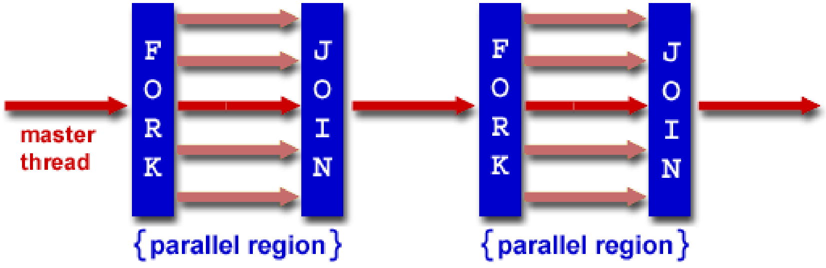
Dr. Eric Strohmaier (University of Tennessee, CS594 class, Feb 9, 2000)

Introduction

- A portable programming model and standard for shared memory programming using compiler directives
- Directives?: constructs or statements in the program applying some action on a block of code
- A specification for a set of compiler directives, library routines, and environment variables – standardizing pragmas
- Easy to program; easy for code developer to convert his sequential to parallel program by throwing directives
- First version in 1997, development over the years till the latest 4.5 in 2015

Fork-Join Model

- Begins as a single thread called master thread
- **Fork**: When **parallel** construct is encountered, team of threads are created
- Statements in the parallel region are executed in parallel
- Join: At the end of the parallel region, the team threads synchronize and terminate



OpenMP consists of…

- Work-sharing constructs
- Synchronization constructs
- Data environment constructs
- Library calls, environment variables

Introduction

- Mainly supports *loop-level parallelism*
- Specifies parallelism for a region of code: *fine-level parallelism*
- The number of threads can be varied from one region to another – *dynamic parallelism*
  - Follows Amdahl's law – sequential portions in the code
  - Applications have varying phases of parallelism
- Also supports
  - Coarse-level parallelism – sections and tasks
  - Executions on accelerators
  - SIMD vectorizations
  - task-core affinity

parallel construct

#pragma omp parallel *[clause [, clause] …] new-line*

structured-block

Clause:

if(*[***parallel :***] scalar-expression*)

num_threads(*integer-expression*)

default(**shared** | **none**)

private(*list*)

firstprivate(*list*)

shared(*list*)

copyin(*list*)

reduction(*reduction-identifier* **:** *list*)

proc_bind(**master** | **close** | **spread**)

Can support nested parallelism

Parallel construct - Example

```
#include <omp.h>

main () {
int nthreads, tid;

    #pragma omp parallel private(nthreads, tid) {

       printf("Hello World \n);
    }

}
```

Work sharing construct

- For distributing the execution among the threads that encounter it
- 3 types of work sharing constructs – loops, sections, single

for construct

- For distributing the iterations among the threads

#pragma omp for *[clause [, clause] …] new-line*
for-loop
Clause:

private (*list*)
firstprivate (*list*)
lastprivate (*list*)
linear (*list[: linear-step]*)
reduction (*reduction-identifier : list*)
schedule (*[modifier [, modifier] :]kind[, chunk_size]*)
collapse (*n*)
ordered*[(n)]*
nowait

for construct

- Restriction in the structure of the for loop so that the compiler can determine the number of iterations – e.g. no branching out of loop
- The assignment of iterations to threads depends on the **schedule** clause
- Implicit barrier at the end of **for** if not **nowait**

schedule clause

1. schedule(static, *chunk_size*) – iterations/chunk_size chunks distributed in round-robin
2. Schedule(dynamic, *chunk_size*) – same as above, but chunks distributed dynamically.
3. schedule(runtime) – decision at runtime. Implementation dependent

for - Example

```
include <omp.h>
#define CHUNKSIZE 100
#define N 1000

main () {
int i, chunk; float a[N], b[N], c[N];

/* Some initializations */
for (i=0; i < N; i++)
  a[i] = b[i] = i * 1.0;

chunk = CHUNKSIZE;
#pragma omp parallel shared(a,b,c,chunk) private(i) {
  #pragma omp for schedule(dynamic,chunk) nowait
    for (i=0; i < N; i++)
      c[i] = a[i] + b[i];
    } /* end of parallel section */

}
```

Coarse level parallelism – sections and tasks

- sections

```
#pragma omp parallel sections \<clause-list\>
{
  #pragma omp section
    structure-block i
  #pragma omp section
    structure-block j
  ...
}
```

- tasks – dynamic mechanism

```
#pragma omp parallel \<clause-list\>
{
...
  #pragma omp task \<clause-list\>
...
}
```

- depend clause for task

```
depend (dependence type : variable\_list)
```

Synchronization directives

```
#pragma omp master new-line
         structured-block
```

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

```
#pragma omp barrier new-line
```

```
#pragma omp atomic new-line
     expression-stmt
```

```
#pragma omp flush [(variable-list)] new-line
```

```
#pragma omp ordered new-line
            structured-block
```

flush directive

- Point where consistent view of memory is provided among the threads
- Thread-visible variables (global variables, shared variables etc.) are written to memory
- If var-list is used, only variables in the list are flushed

flush - Example

```
int    sync[NUMBER_OF_THREADS];
float work[NUMBER_OF_THREADS];
#pragma omp parallel private(iam,neighbor) shared(work,sync)
{

   iam = omp_get_thread_num();
   sync[iam] = 0;
   #pragma omp barrier

   /*Do computation into my portion of work array */
   work[iam] = ...;

   /*  Announce that I am done with my work
    *  The first flush ensures that my work is
    *  made visible before sync.
    *  The second flush ensures that sync is made visible.
    */
```

flush – Example (Contd…)

```
  #pragma omp flush(work)
  sync[iam] = 1;
  #pragma omp flush(sync)

  /*Wait for neighbor*/
  neighbor = (iam>0 ? iam : omp_get_num_threads()) - 1;
  while (sync[neighbor]==0) {
    #pragma omp flush(sync)
  }

  /*Read neighbor's values of work array */
  ... = work[neighbor];
}
```

Data Scope Attribute Clauses

Most variables are shared by default

Data scopes explicitly specified by data scope attribute clauses

Clauses:

1. private
2. firstprivate
3. lastprivate
4. shared
5. default
6. reduction
7. copyin
8. copyprivate

threadprivate

- Global variable-list declared are made private to a thread
- Each thread gets its own copy
- Persist between different parallel regions

```
#include <omp.h>
int alpha[10], beta[10], i;
#pragma omp threadprivate(alpha)
main () {
  /* Explicitly turn off dynamic threads */
  omp_set_dynamic(0);
  /* First parallel region */
  #pragma omp parallel private(i,beta)
  for (i=0; i < 10; i++) alpha[i] = beta[i] = i;
  /* Second parallel region */
  #pragma omp parallel
  printf("alpha[3]= %d and beta[3]= %d\n",alpha[3],beta[3]);}
```

private, firstprivate & lastprivate

- private (*variable-list*)
- variable-list private to each thread
- A new object with automatic storage duration allocated for the construct

- firstprivate (*variable-list*)
- The new object is initialized with the value of the old object that existed prior to the construct

- lastprivate (*variable-list*)
- The value of the private object corresponding to the last iteration or the last section is assigned to the original object

shared, default, reduction

- shared(*variable-list*)

- default(shared | none)
- Specifies the sharing behavior of all of the variables visible in the construct

- Reduction(*op: variable-list*)
- Private copies of the variables are made for each thread
- The final object value at the end of the reduction will be combination of all the private object values

default - Example

```
int x, y, z[1000];
#pragma omp threadprivate(x)

void fun(int a) {
  const int c = 1;
  int i = 0;

  #pragma omp parallel default(none) private(a) shared(z)
  {
      int j = omp_get_num_thread();
              //O.K.  - j is declared within parallel region
          a = z[j];

          x = c;

          z[i] = y;
```

Library Routines (API)

- Querying function (number of threads etc.)
- General purpose locking routines
- Setting execution environment (dynamic threads, nested parallelism etc.)

API

- OMP_SET_NUM_THREADS(num_threads)
- OMP_GET_NUM_THREADS()
- OMP_GET_MAX_THREADS()
- OMP_GET_THREAD_NUM()
- OMP_GET_NUM_PROCS()
- OMP_IN_PARALLEL()
- OMP_SET_DYNAMIC(dynamic_threads)
- OMP_GET_DYNAMIC()
- OMP_SET_NESTED(nested)
- OMP_GET_NESTED()

API(Contd..)

- omp_init_lock(omp_lock_t *lock)
- omp_init_nest_lock(omp_nest_lock_t *lock)
- omp_destroy_lock(omp_lock_t *lock)
- omp_destroy_nest_lock(omp_nest_lock_t *lock)
- omp_set_lock(omp_lock_t *lock)
- omp_set_nest_lock(omp_nest_lock_t *lock)
- omp_unset_lock(omp_lock_t *lock)
- omp_unset_nest__lock(omp_nest_lock_t *lock)
- omp_test_lock(omp_lock_t *lock)
- omp_test_nest_lock(omp_nest_lock_t *lock)

- omp_get_wtime()
- omp_get_wtick()

- omp_get_thread_num()
- omp_get_num_proc()
- omp_get_num_devices()

Lock details

- Simple locks and nestable locks
- Simple locks are not locked if they are already in a locked state
- Nestable locks can be locked multiple times by the same thread
- Simple locks are available if they are unlocked
- Nestable locks are available if they are unlocked or owned by a calling thread

Example – Nested lock

```
#include <omp.h>
typedef struct {int a,b; omp_nest_lock_t lck;} pair;

void incr_a(pair *p, int a)
{
  // Called only from incr_pair, no need to lock.
  p->a += a;
}

void incr_b(pair *p, int b)
{
  // Called both from incr_pair and elsewhere,
  // so need a nestable lock.

  omp_set_nest_lock(&p->lck);
  p->b += b;
  omp_unset_nest_lock(&p->lck);
}
```

Example – Nested lock (Contd..)

```
void incr_pair(pair *p, int a, int b)
{
  omp_set_nest_lock(&p->lck);
  incr_a(p, a);
  incr_b(p, b);
  omp_unset_nest_lock(&p->lck);
}

void f(pair *p)
{
  extern int work1(), work2(), work3();
  #pragma omp parallel sections
  {
    #pragma omp section
      incr_pair(p, work1(), work2());
    #pragma omp section
      incr_b(p, work3());
  }
}
```

Example 1: Jacobi Solver

```
#include "omp.h"
int main(int argc, char** argv){
...
int rows, cols;
int* grid;
int chink_size, threads=16;
...

    /* Allocate and initialize the grid */
    grid = malloc(sizeof(int*)*N*N);
    for(i=0; i<N; i++){
      for(j=0; j<N; j++){
        grid[i*cols+j] = ...;
      }
    }

    chunk_size = N/threads;
    # pragma omp parallel for num_threads(16) for private(i,j)
        shared(rows,cols,grid) schedule(static,chunk_size)
        collapse(2)
      for(i=1; i<rows-1; i++){
        for(j=1; j<cols-1; j++){
          grid[i*N+j] = 1/4 * (grid[i*N+j-1] + grid[i*N+j+1] +
                  grid[(i-1)*N+j] + grid[(i+1)*N+j]);
        }
      }
```

Example 2: BFS Version 1 (Nested Parallelism)

```
...
  level[0] = s;
  curLevel = 0;
  dist[s]=0; dist[v!=s]=-1;

  while(level[curLevel] != NULL){
    # pragma omp parallel for ....
      for(i=0; i<length(level[curLevel]); i++){
        v=level[curLevel][i];
        neigh=neighbors(v);

      # pragma omp parallel for ....
        for(j=0; j<length(neigh); j++){
          w=neigh[j];
          if(dist[w] =    1 ){
            level[curLevel + 1] = union(level[curLevel + 1], w);
            dist[w]      dist[v] + 1;
          }
        }
      }
  }
...
```

Example 3: BFS Version 3 (Using Task Construct)

```
...
  level[0] = s;
  curLevel = 0;
  dist[s]=0; dist[v!=s]=-1;

  while(level[curLevel] != NULL){
    # pragma omp parallel ....
      for(v in level[curLevel]){
        for(w in neighbors(v)){
          # pragma omp task...
          {
            if(dist[w] =   1 ){
              level[curLevel + 1] = union(level[curLevel + 1], w)
                  ;
              dist[w]     dist[v] + 1;
            }
          }
        }
      }
  }
...
```

Hybrid Programming – Combining MPI and OpenMP benefits

- MPI
  - explicit parallelism, no synchronization problems
  - suitable for coarse grain
- OpenMP
  - easy to program, dynamic scheduling allowed
  - only for shared memory, data synchronization problems
- MPI/OpenMP Hybrid
  - Can combine MPI data placement with OpenMP fine-grain parallelism
  - Suitable for cluster of SMPs (Clumps)
  - Can implement hierarchical model

- END

Definitions

- Construct – statement containing directive and structured block
- Directive – Based on C #pragma directives

#pragma <omp id> <other text>

#pragma omp *directive-name [clause [, clause] …] new-line*

Example:

#pragma omp parallel default(shared) private(beta,pi)

Parallel construct

- Parallel region executed by multiple threads
- If num_threads, omp_set_num_threads(), OMP_SET_NUM_THREADS not used, then number of created threads is implementation dependent
- Number of physical processors hosting the thread also implementation dependent
- Threads numbered from 0 to N-1
- Nested parallelism by embedding one parallel construct inside another