OPENMP

Course “Parallel Computing”

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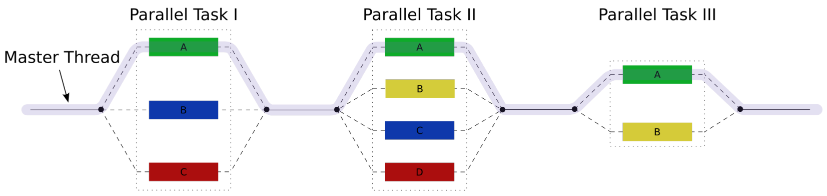
OpenMP (OMP)

- An API for portable shared memory parallel programming.
  - Compiler directives (pragmas), library routines, environment variables.
- Targets are C, C++, Fortran.
  - Often used in combination with MPI (Message Passing Interface) for hybrid MPP/SMP programs.
- Widely supported.
  - Commercial compilers: Intel, IBM, Oracle, …
  - Free compilers: GCC, Clang.
- Maintained by the OpenMP ARB.
  - Architecture Review Board.
  - Current Version: OpenMP 6.0 (November 2024).

See `http://openmp.org` for the official specification.

Programming Model



en.wikipedia.org, *OpenMP*

- Master thread executes program in sequential mode.
- Reaches code section marked with OMP directive:
  - Execution of section is distributed among multiple threads.
  - Main thread waits for completion of all threads.
  - Execution is continued by main thread only.

A fork-join model of parallel execution.

Shared versus Private Variables

The default context of a variable is determined by some rules.

- Static variables and heap-allocated data are shared.
- Automatically allocated variables are
  - Shared, when declared outside a parallel region.
  - Private, when declared inside a parallel region.
- Loop iteration variables are private within their loops.
  - After the loop, the variable has the same value as if the loop would have been executed sequentially.
- …

OpenMP clauses may specify the context of variables directly.

OpenMP Memory Consistency

```
The following rules guarantee the observable completion order of memory operations,
as seen by all threads.

    If two operations performed by different threads are sequentially consistent atomic operations
    or they are strong flushes that flush the same variable, then they must be completed as if
    in some sequential order, seen by all threads.

    If two operations performed by the same thread are sequentially consistent atomic operations
    or they access, modify, or, with a strong flush, flush the same variable, then they must be
    completed as if in that thread's program order, as seen by all threads.

    If two operations are performed by different threads and one happens before the other,
    then they must be completed as if in that happens before order, as seen by all threads, if:
        both operations access or modify the same variable;
        both operations are strong flushes that flush the same variable; or
        both operations are sequentially consistent atomic operations.

    Any two atomic memory operations from different atomic regions must be completed as if in the
    same order as the strong flushes implied in their respective regions, as seen by all threads.

The flush operation can be specified using the flush directive, and is also implied at
various locations in an OpenMP program: see Section 2.17.8 on page 677 for details.
```

In short, consider the “happens-before” relationship.

Controlling the Number of Threads

- Default set by environment variables:

```
export OMP_DYNAMIC=FALSE
export OMP_NUM_THREADS=4
```

- May be overridden for all subsequent code sections:

```
omp_set_dynamic(0);
omp_set_num_threads(4);
```

- May be overridden for specific sections:

```
#pragma omp parallel ... num_threads(4)
```

If dynamic adjustement is switched on, the actual number of threads executing a section may be smaller than specified.

Controlling the Affinity of Threads to Cores

- Pin threads to cores:

  ```
  export OMP_PROC_BIND=TRUE
  ```

- Specify the cores (GCC, Intel Compilers):

  ```
  export GOMP_CPU_AFFINITY="256-271" // 16 physical cores in upper half
  ```

- More flexible alternative for Intel compilers:

  ```
    export KMP_AFFINITY=
      "verbose,granularity=core,explicit,proclist=[256-271]"
  ```

Compiling and Executing OpenMP

- Source

```
#include <omp.h>
```

- Intel Compiler:

```
module load intelcompiler/composer_xe_2013.4.183
icc -Wall -O3 -openmp -openmp-report2 matmult.c -o matmult
```

- GCC:

```
module load GnuCC/7.2.0
gcc -Wall -O3 -fopenmp matmult.c -o matmult
```

- Execution:

```
export OMP_DYNAMIC=FALSE
export OMP_NUM_THREADS=16
export GOMP_CPU_AFFINITY="256-271"
./matmult
```

Parallel Loops

```
#pragma omp parallel for private(j,k)
for (i=0; i<N; i++) {
  for (j=0; j<N; j++) {
    for (k=0; k<N; k++) {
       a[i,j] += b[i,k]*c[k,j];
    }
  }
}
```

- Iterations of i-loop are executed by parallel threads.
- Matrix a is shared by all threads.
- Every thread maintains private instances of i, j, k.

Most important source of scalable parallelism.

Load Balancing

```
#pragma omp parallel for ... schedule(kind [, chunk size])
```

- Various kinds of loop scheduling:

static
: Loop is divided into equally sized chunks which are interleaved among threads; default chunk size is N/T.
  - Number of loop iterations N and number of threads T.

dynamic
: Threads retrieve chunks from a shared work queue; default chunk size is 1.

guided
: Like “dynamic” but chunk size starts large and is continuously decremented to specified minimum (default 1).

auto
: One of the above policies is automatically selected (same as if no schedule is given).

runtime
: Schedule taken from environment variable `OMP_SCHEDULE`.

```
export OMP_SCHEDULE="static,1"
```

Example: Matrix Multiplication

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

#define N 2000
double A[N][N], B[N][N], C[N][N];

int main(int argc, char *argv[]) {
  int i, j, k;
  double s;

  for (i=0; i<N; i++)
  {
    for (j=0; j<N; j++)
    {
      A[i][j] = rand();
      B[i][j] = rand();
    }
  }

  printf("%f %f\n", A[0][0], B[0][0]);
  double t1 = omp_get_wtime();
  #pragma omp parallel for private(j,k,s) schedule(runtime)
  for (i=0; i<N; i++)
  {
    for (j=0; j<N; j++)
    {
      s = 0;
      for (k=0; k<N; k++)
      {
        s += A[i][k]*B[k][j];
      }
      C[i][j] = s;
    }
  }

  double t2 = omp_get_wtime();
  printf("%f (%f s)\n", C[0][0], t2-t1);
  return 0;
}
```

Parallel Sections

```
int found1, found2, found3;

#pragma omp parallel sections
{
   #pragma omp section
   found1 = search1();
   #pragma omp section
   found2 = search2();
   #pragma omp section
   found3 = search3();
}

if (found1) printf(‘‘found by method 1\n’’);
if (found2) printf(‘‘found by method 2\n’’);
if (found3) printf(‘‘found by method 3\n’’);
```

- Each code section is executed by a thread in parallel.

Parallel sections and loops may be also nested.

Parallel Blocks

```
int n, a[n], t, i;

#pragma omp parallel private(t, i)
{
  t = omp_get_num_threads(); // number of threads
  i = omp_get_thread_num();  // 0 <= i < t
  compute(a, i*(n/t), min(n, (i+1)*(n/t)));
}
```

- Every thread executes the annotated block.
- Array a and length n are shared by all threads.
- Every thread maintains private instances of t and i.

Parallelism on the lowest level.

Critical Sections

```
int n, a[n], t = 0, i;

#pragma omp parallel private(i)
{
  #pragma omp critical(mutex_i)
  {
    i = t; t++;
  }
  if (i < n) compute(a, i);
}
```

- No two threads can simultaneously execute a critical section with the same name.

High-level but restricted synchronization.

Example: Manual Task Scheduling

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

#define N 2000
double A[N][N], B[N][N], C[N][N];

int main(int argc, char *argv[])
{
  int i, j, k, row;
  double s;

  for (i=0; i<N; i++)
  {
    for (j=0; j<N; j++)
    {
      A[i][j] = rand();
      B[i][j] = rand();
    }
  }

  printf("%f %f\n", A[0][0], B[0][0]);
  double t1 = omp_get_wtime();
  row = 0;
  #pragma omp parallel private(i,j,k,s)
  {
    while (1)
    {
      #pragma omp critical(getrow)
      {
        i = row;
        row++;
      }
      if (i>=N) break;
      for (j=0; j<N; j++)
      {
        s = 0;
        for (k=0; k<N; k++)
        {
          s += A[i][k]*B[k][j];
        }
        C[i][j] = s;
      }
    }
  }
  double t2 = omp_get_wtime();
  printf("%f (%f s)\n", C[0][0], t2-t1);
  return 0;
}
```

Lock Variables

```
int n, a[n], t = 0, i;
omp_lock_t lock;
omp_init_lock(lock);

#pragma omp parallel private(i)
{
  omp_set_lock(lock);
  i = t; t++;
  omp_unset_lock(lock);
  if (i < n) compute(a, i);
}
```

- Only one thread can set a lock at a time.

Flexible but low-level synchronization.

Example: Recursive Tasks

```
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>

#define N 3000
double A[N][N], B[N][N], C[N][N];

int matmultrec(int begin, int end);
int matmultrow(int i);

int main(int argc, char *argv[])
{
  int i, j, r;
  double t1, t2;
  for (i=0; i<N; i++) {
    for (j=0; j<N; j++) {
      A[i][j] = rand();
      B[i][j] = rand();
    }
  }
  printf("%f %f\n", A[0][0], B[0][0]);
  t1 = omp_get_wtime();

  #pragma omp parallel
  {
   #pragma omp single
   {
     r = matmultrec(0, N);
   }
  }

  t2 = omp_get_wtime();
  printf("%d %f (%f s)\n",
    r, C[0][0], t2-t1);
  return 0;
}
```

Example: Recursive Tasks

```
int matmultrec(int begin, int end)
{
  int n = end-begin;
  if (n < 0) return 0;
  if (n == 1)
    return matmultrow(begin);
  int mid = (begin+end)/2;
  int r1, r2;
  #pragma omp task shared(r1)
  r1 = matmultrec(begin, mid);
  #pragma omp task shared(r2)
  r2 = matmultrec(mid, end);
  #pragma omp taskwait
  return r1+r2;
}
```

```
int matmultrow(int i)
{
  int j, k;
  double s;
  for (j = 0; j < N; j++)
  {
    s = 0;
    for (k = 0; k < N; k++)
    {
      s += A[i][k]*B[k][j];
    }
    C[i][j] = s;
  }
  return 1;
}
```

- Recursively create two tasks and wait for their completion.

Also (recursive) task parallelism is possible.