

# OPENMP

## Course “Parallel Computing”



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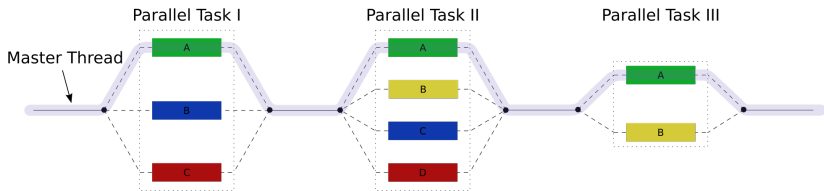


# OpenMP (OMP)

- 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 5.2 (November 2021).

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.

# 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 adjustment 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.

# Tasks

```
int main(int argc, char* argv[])
{
    #pragma omp parallel
    {
        #pragma omp single
        {
            int n = 1000000;
            int* a =
                malloc(n*sizeof(int));
            int r =
                compute(a, 0, n-1);
        }
    }
}

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

- Recursively create two tasks and wait for their completion.

Task parallelism possible, but may become cumbersome.