CISC 372: Parallel Computing
OpenMP, Part 3

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OpenMP worksharing directives

Recall:

- used to divide up work among threads
- kinds of work-sharing constructs
  - for loops: distribute iterations to team members
  - sections: distribute independent code bocks (work units)
  - single: let only one thread execute a block

We left off looking at different clauses that can be used with the `omp for` directive.

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

- this is another clause that can be added to an `omp for` directive
- performs an (approximately) associative and commutative operation across all threads
- each variable v in the list should be a shared variable
- v should be initialized before entering the loop
- effectively, a private copy of v is created
- each private v is initialized to the default initial value corresponding to the operation
  - 0 for $+$, 1 for $*$, etc.
- all operations in loop body take place on the private copies
- when a thread finishes its iterations:
  - it adds (or whatever the operation is) its private value back to the shared v
  - this happens atomically to prevent races

Reduction example: `reduce.c`

```c
#include <stdio.h>
#include <omp.h>
#define n 10
int a[n], s=1000000;
int main() {
  printf("Start s = %d\n", s);
#pragma omp parallel default(none) shared(a,s)
  {
    int tid = omp_get_thread_num();
#pragma omp for
    for (int i=0; i<n; i++) a[i] = i;
#pragma omp for reduction(+:s) schedule(static,1)
    for (int i=0; i<n; i++) {
      s+=a[i];
      printf("Local s on thread %d = %d\n", tid, s);
    }
  }
  printf("Final s = %d\n", s);
}
```

Reduction example: output

```
  omp$ make reduce
cc -fopenmp -o reduce.exec reduce.c
./reduce.exec
Start s = 1000000
Local s on thread 0 = 0
Local s on thread 0 = 2
Local s on thread 0 = 6
Local s on thread 0 = 12
Local s on thread 0 = 20
Local s on thread 1 = 1
Local s on thread 1 = 4
Local s on thread 1 = 9
Local s on thread 1 = 16
Local s on thread 1 = 25
Final s = 1000045
omp$
```

Reduction operations

operation	operator	initial value
addition	`+`	0
multiplication	`*`	1
subtraction (?)	`-`	0
bitwise and	`&`	~0
bitwise or	`|`	0
bitwise exclusive or	`^`	0
logical and	`&&`	1
logical or	`||`	0

Controlling loop schedules: `schedule(static, chunk_size)`

- iterations are partitioned into chunks of size *chunk_size*
- chunks are distributed in round-robin order to threads
- last chunk may be smaller
- distribution is "static": determined upon reaching the loop
- you can omit *chunk_size*
  - iteration space divided into chunks of approximately equal size
  - at most one chunk given to each thread

Controlling loop schedules: `schedule(dynamic, chunk_size)`

- iterations are partitioned into chunks of size *chunk_size*
- chunks are distributed to threads as they request them
  - similar to the "manager-worker" pattern
  - as soon as a thread completes its chunk, it asks for a new one
- last chunk may be smaller
- advantageous when time to execute an iteration varies in an unpredictable way
- distribution is "dynamic": determined as loop executes

Controlling loop schedules: `schedule(guided, chunk_size)`

- this is a variation on *dynamic* in which the chunk size decreases as execution proceeds
- size of chunk proportional to number of unassigned iterations divided by number of threads
  - *chunk_size* is a lower bound on the size of a chunk
  - for *chunk_size* $= 1$, size of a chunk decreases to 1
  - for *chunk_size* $= k > 1$, all chunks other than last must contain at least k iterations
- motivation
  - there is overhead to the manager-worker protocol
  - bigger chunks $\rightarrow$ less overhead, but greater probability of leaving a thread idle
  - compromise: increase granularity as iteration space gets smaller, when the chance of leaving a thread idle is greater

To wait or not to wait?

- use of `nowait` clause in `for` directive removes the implicit barrier at end of loop
- this can increase concurrency, and performance
- but can also introduce bugs
  - use with extreme caution
  - make sure it does not introduce data races

To wait or not to wait: `wait1.c`

```
int main () {
  double a[n], b[n];
#pragma omp parallel default(none) shared(a,b)
  {
#pragma omp for nowait
    for (int i=0; i<n; i++)
      a[i] = 2.0*i;
#pragma omp for
    for (int i=0; i<n; i++)
      b[i] = 3.0*i;
  } /* end of parallel region */
  for (int i=0; i<n; i++) {
    if (a[i]!=2.0*i) { printf("Error at a[%d]: %f\n", i, a[i]); fflush(stdout); exit(1); }
    if (b[i]!=3.0*i) { printf("Error at b[%d]: %f\n", i, b[i]); fflush(stdout); exit(1); }
  }
  printf("Success\n");
}
```

- OK: the two loops can execute concurrently since they update distinct variables

To wait or not to wait: `wait2.c`

```
int main() {
  double a[n], b[n];
#pragma omp parallel default(none) shared(a,b)
  {
#pragma omp for nowait
    for (int i=0; i<n; i++) a[i] = 2.0*i;
#pragma omp for
    for (int i=0; i<n; i++) b[i] = 2.0*a[n-i-1];
  } /* end of parallel region */
  for (int i=0; i<n; i++) {
    if (a[i] != 2.0*i) {
      printf("Error at a[%d]: %f\n", i, a[i]); fflush(stdout); exit(1);
    }
    if (b[i] != 2.0*(2.0*(n-i-1))) {
      printf("Error at b[%d]: %f\n", i, b[i]); fflush(stdout); exit(1);
    }
  }
  printf("Success 2\n");
}
```

- NOT OK: second loop reads variables assigned in the first loop. Run it, and then run `wait2_fix.c`.

Worksharing constructs: `sections`

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

- specifies explicit code blocks which can execute in parallel
- each block (or section) is executed once, by exactly one thread
- a thread may execute several sections, or no sections
- in general: you cannot assume anything about how sections are distributed to threads
- barrier at end (unless overridden with `nowait`)

sections example: sections.c, part 1

```
#include <stdio.h>
#include <omp.h>
#include <limits.h>
#define N 20
typedef unsigned long ulong;

ulong sumUpTo(int n) {
  ulong s=0;
  for (int i=1; i<=n; i++) s+=i;
  return s;
}

ulong productUpTo(int n) {
  ulong p=1;
  for (int i=1; i<=n; i++) p*=i;
  return p;
}
```

sections example: sections.c, part 2

```
int main() {
#pragma omp parallel
  { /* begin parallel region */
    int tid = omp_get_thread_num();
    if (tid == 0) printf("Number of threads: %d\n", omp_get_num_threads());
#pragma omp sections
    { /* begin sections */
#pragma omp section
      {
        printf("Thread %d: sum to %d ........... %lu\n", tid, N, sumUpTo(N));
      }
#pragma omp section
      {
        printf("Thread %d: product to %d ....... %lu\n", tid, N, productUpTo(N));
      }
    } /* end of sections */
  } /* end of parallel region */
}
```

Clauses allowed with `sections`

- `private(list)`
  - each section has its own private copy of variable
- `firstprivate(list)`
  - make private and initialize with shared variable value
- `lastprivate(list)`
  - value of private copy of variable in last section is copied to shared variable at end
- `reduction(reduction-identifier:list)`
  - reduction applied across all sections
- `nowait`
  - removes barrier at end

Worksharing constructs: `single`

```
#pragma omp single
S
```

- indicates that you want only one thread in the team to execute S
  - you don't care which thread
- barrier at end (unless overridden with `nowait`)
- typical use: initialization of shared variable

Clauses:

- `private(list)`, `firstprivate(list)`, `nowait`: usual semantics
- `copyprivate(list)`
  - applies to private variables
  - copies final value of variable in the single thread to corresponding variables in all other threads
  - copy occurs at end, before threads leave the barrier