Advanced OpenMP

Memory model, flush and atomics

Why do we need a memory model?

- On modern computers code is rarely executed in the same order as it was specified in the source code.
- Compilers, processors and memory systems reorder code to achieve maximum performance.
- Individual threads, when considered in isolation, exhibit *as-if-serial* semantics.
- Programmer's assumptions based on the memory model hold even in the face of code reordering performed by the compiler, the processors and the memory.

Example

- Reasoning about multithreaded execution is not that simple.

```
T1    T2
x=1;  int r1=y;
y=1;  int r2=x;
```

- If there is no reordering and *T2* sees value of *y* on read to be 1 then the following read of *x* should also return the value 1. If code in *T1* is reordered we can no longer make this assumption.

OpenMP Memory Model

- OpenMP supports a relaxed-consistency shared memory model.
  - Threads can maintain a temporary view of shared memory which is not consistent with that of other threads.
  - These temporary views are made consistent only at certain points in the program.
  - The operation which enforces consistency is called the flush operation

Flush operation

- Defines a sequence point at which a thread is guaranteed to see a consistent view of memory
  - All previous read/writes by this thread have completed and are visible to other threads
  - No subsequent read/writes by this thread have occurred
  - A flush operation is analogous to a fence in other shared memory API's

Flush and synchronization

- A flush operation is implied by OpenMP synchronizations, e.g.
  - at entry/exit of parallel regions
  - at implicit and explicit barriers
  - at entry/exit of critical regions
  - whenever a lock is set or unset

  ….

  (but not at entry to worksharing regions or entry/exit of master regions)

- Note: using the **`volatile`** qualifier in C/C++ does *not* give sufficient guarantees about multithreaded execution.

Example: producer-consumer pattern

Thread 0

```
a = foo();
flag = 1;
```

Thread 1

```
while (!flag);
b = a;
```

- This is incorrect code
- The compiler and/or hardware may re-order the reads/writes to a and flag, or flag may be held in a register.
- OpenMP has a flush directive which specifies an explicit flush operation
  - can be used to make the above example work

```
!$omp flush
```

```
#pragma omp flush
```

Using flush

- In order for a write of a variable on one thread to be guaranteed visible and valid on a second thread, the following operations must occur in the following order:

1. Thread A writes the variable
2. Thread A executes a flush operation
3. Thread B executes a flush operation
4. Thread B reads the variable

Example: producer-consumer pattern

Thread 0

```
a = foo();
#pragma omp flush
flag = 1;
#pragma omp flush
```

Thread 1

```
#pragma omp flush
while (!flag){
#pragma omp flush
}
#pragma omp flush
b = a;
```

First flush ensures `flag` is written after `a`

Second flush ensures `flag` is written to memory

First and second flushes ensure `flag` is read from memory

Third flush ensures correct ordering of flushes

Using flush

- Using flush correctly is difficult and prone to subtle bugs
  - extremely hard to test whether code is correct
  - may execute correctly on one platform/compiler but not on another
  - bugs can be triggered by changing the optimisation level on the compiler

- Don't use it unless you are 100% confident you know what you are doing!
  - and even then……

ATOMIC directive

- Used to protect a single update to a shared variable.
- Applies only to a single statement.
- Syntax:

Fortran: **`!$OMP ATOMIC`**

statement

where *statement* must have one of these forms:

x = *x op expr*, *x* = *expr op x*, *x* = *intr* **(***x*, *expr***)** or

x = *intr* **(***expr*, *x***)**

op is one of **`+`**, **`*`**, **`-`**, **`/`**, **`.and.`**, **`.or.`**, **`.eqv.`**, or **`.neqv.`**

intr is one of **`MAX`**, **`MIN`**, **`IAND`**, **`IOR`** or **`IEOR`**

ATOMIC directive (cont)

C/C++: **`#pragma omp atomic`**

statement

where *statement* must have one of the forms:

x binop **=** *expr*, *x***++**, **++***x*, *x***--**, or **--***x*

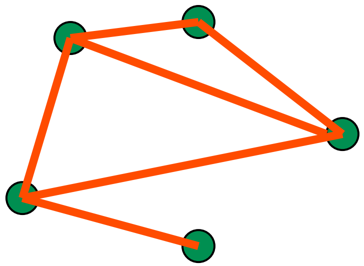
and *binop* is one of **+**, *****, **-**, **/**, **&**, **^**, **<<**, or **>>**

- Note that the evaluation of *expr* is not atomic.
- May be more efficient than using CRITICAL directives, e.g. if different array elements can be protected separately.
- No interaction with CRITICAL directives

ATOMIC directive (cont)

Example (compute degree of each vertex in a graph):

```
#pragma omp parallel for
      for (j=0; j<nedges; j++){
#pragma omp atomic
         degree[edge[j].vertex1]++;
#pragma omp atomic
         degree[edge[j].vertex2]++;
      }
```



Other atomic forms

- Sometimes we may wish to enforce atomic behaviour for operations other than updates

```c
#pragma omp atomic read
   v = x;

#pragma omp atomic write
   x = expr;

#pragma omp atomic capture
{v = x; x binop= expr;}
```

```fortran
!$omp atomic read
   v = x

!$omp atomic write
   x = expr

!$omp atomic capture
   v = x
   x = x op expr
!$omp end atomic
```

Example: producer-consumer pattern

Thread 0

```
a = foo();
#pragma omp flush
#pragma omp atomic write
flag = 1;
#pragma omp flush
```

Thread 1

```
#pragma omp flush
while (!myflag){
#pragma omp flush
#pragma omp atomic read
   myflag = flag;
}
#pragma omp flush
b = a;
```

To be strictly correct we should use atomics to avoid the race condition on `flag`.