OpenMP Runtime Error Detection with ARCHER

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Data race example in OpenMP

```
static double farg1,farg2;
#define FMAX(a,b) (farg1=(a),farg2=(b),farg1>farg2?farg1:farg2)
```

What could possibly go wrong?

To avoid side effects, the arguments are copied to temporary storage

Double checked scoping of variables: everything seems to be fine

```
1619: #pragma omp parallel for shared(bar, foo, THRESH)
1620: for (x=0; x<1000; x++)
1621:   T = FMAX(0.1111*foo*bar[x],THRESH);
```

Tool flags a write-write race in line 1621

What could possibly go wrong?

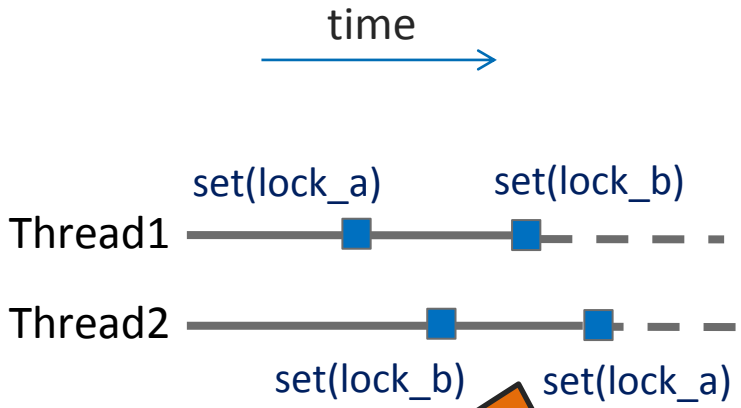
Threaded Applications (OpenMP)
Threaded Defects

Threaded Applications (OpenMP)
Threaded Defects – Deadlock

A circular wait condition exists in the system that causes two or more parallel units to wait indefinitely

```
#pragma omp parallel sections
{
        #pragma omp section
        {
                omp_set_lock(&lock_a);
                omp_set_lock(&lock_b);
                omp_unset_lock(&lock_b);
                omp_unset_lock(&lock_a);
        }
        #pragma omp section
        {
                omp_set_lock(&lock_b);
                omp_set_lock(&lock_a);
                omp_unset_lock(&lock_a);
                omp_unset_lock(&lock_b);
        }
}
```

Deadlocking Execution Order



- Thread 1 waits for lock_b owned by thread 2
- Thread 2 waits for lock_a, owned by Thread 1.
- Neither thread can free a lock and both threads wait indefinitely.

Threaded Applications (OpenMP)
Threaded Defects – Data Race

Program behavior dependent on execution order of threads/processes

```
int x,y;
#pragma omp parallel
{
        x = omp_get_thread_num ();
        #pragma omp barrier
        #pragma omp master
                printf (“Master is:%d” ,x);
}
```

A write-write race on x

```
int x,y;
#pragma omp parallel
{
        #pragma omp master
                sleep(5);
        x = omp_get_thread_num ();
        #pragma omp barrier
        #pragma omp master
                printf (“Master is:%d” ,x);
}
```

If the master thread is intended to write x, it will usually do so, due to the sleep; But sometimes it may not …

Threaded Applications (OpenMP) Definitions

Data race

- Two threads access the same shared variable
  - at least one thread modifies the variable
  - the accesses are concurrent, i.e. unsynchronized
- Leads to non-deterministic behavior
- Hard to find with traditional debugging tools

Deadlock

- Two or more threads are waiting for each other to release locks while holding the lock the other leads to non-deterministic behavior
- Program hangs
- May be non-deterministic

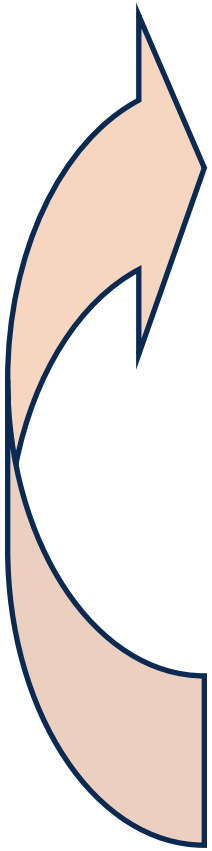
Threaded Applications (OpenMP)
Archer

- Error checking tool for
  - Memory errors
  - **Threading errors**
    (OpenMP, Pthreads)
- Based on ThreadSanitizer (runtime check)
- Available for Linux, Windows and Mac
- Supports C, C++ (Fortran in work)
- Modified OpenMP runtime improved for data race detection
- More info: https://github.com/PRUNERS/archer

Threaded Applications (OpenMP)
Archer – Background

- Static Analysis
  - Only for OpenMP programs
  - Exclude race free regions and sequential code from runtime analysis to reduce overhead
- Runtime check
  - Error detection only in software branches that are executed
- Low runtime overhead
  - Roughly 2x - 20x
  - Detect races in large OpenMP applications
  - No false positives
- Compiler instrumentation
  - Slower compilation process (apply different passes on the source code to identify race free regions of code, instruments only the rest)

Threaded Applications (OpenMP)
Archer – Usage



- Compile the program with the –g compiler flag
  - `clang-archer myprog.c –o myprog`
- Run the program under control of ARCHER Runtime
  - `export OMP_NUM_THREADS=...`
    `./myprog`
  - Detects problems only in software branches that are executed
- Understand and correct the threading errors detected
- Edit the source code
- Repeat until no errors reported

Threaded Applications (OpenMP)
Archer – Result Summary

```
 1  #include <stdio.h>
 2
 3  int main(int argc, char **argv) {
 4      int a = 0;
 5      #pragma omp parallel
 6      {
 7          if (a < 100) {
 8              #pragma omp critical
 9              a++;
10          }
11      }
12  }
```

```
WARNING: ThreadSanitizer: data race
Read of size 4 at 0x7fffffffdcdc by thread T2:
    #0 .omp_outlined. race.c:7
(race+0x0000004a6dce)
    #1 __kmp_invoke_microtask <null>
(libomp_tsan.so)

Previous write of size 4 at 0x7fffffffdcdc by
main thread:
    #0 .omp_outlined. race.c:9
(race+0x0000004a6e2c)
    #1 __kmp_invoke_microtask <null>
(libomp_tsan.so)
```

Using Archer on Claix

```
$ module load archer
```

Use NPB-OMP, modify config/make.def to use clang-archer:

Line 78: `CC = clang-archer`

Build IS or DC:

```
$ make dc CLASS=W
$ OMP_NUM_THREADS=8 bin/dc.W.x
```

No report means no threading-issue detected ☺

Hands-on

```
$ module load archer

$ cp -r ~hpclab11/tutorial/archer archer-examples
$ cd archer-examples
$ clang -fopenmp –g prime_omp.c -lm
```

Try:

```
$ OMP_NUM_THREADS=2 ./a.out
$ OMP_NUM_THREADS=4 ./a.out
$ OMP_NUM_THREADS=8 ./a.out
```

Hands-on 2

- Now compile with data race detection:

```
$ clang-archer prime_omp.c
$ OMP_NUM_THREADS=2 ./a.out
```

Fix the issues, recompile, test again

For extensive testing: do this using the batch system

Fallback and usage for Fortran-code

- In cases, where compilation with clang-archer fails:

```
$ clang –fsanitize=thread -fopenmp –g prime_omp.c
```

or

```
$ clang –fsanitize=thread -fopenmp –g –c prime_omp.c
$ clang –fsanitize=thread -fopenmp prime_omp.o
```

or

```
$ gfortran –fsanitize=thread -fopenmp –g –c prime_omp.f
$ clang –fsanitize=thread -fopenmp –lgfortran prime_omp.o

$ OMP_NUM_THREADS=2 ./a.out
```

For OpenMP programs, always use the clang delivered with ARCHER to avoid false alerts

Release of Archer 1.0

- Just finished two days ago.
- Improved accuracy regarding OpenMP tasks
- Now building on OMPT, and therefore portable across OpenMP runtimes

- Now also available on OpenPower architecture, so will be available on next generation HPC systems

Conclusions

- Deadlocks:
  - Avoid locks when possible
  - Prefer critical/master/…
- Races:
  - Often hard to detect, in many cases only visible from time to time
  - Races manifesting only at large scale are often detectable by ARCHER at small scale
  - (Fortran) consider: default(private)
- Use tools to detect defects as early as possible:
  - During development + unit testing
  - Development of ARCHER is ongoing effort, also porting to more architectures and OpenMP runtimes.

Thank You