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);
```

What could possibly go wrong?

Tool flags a write-write race in line 1621

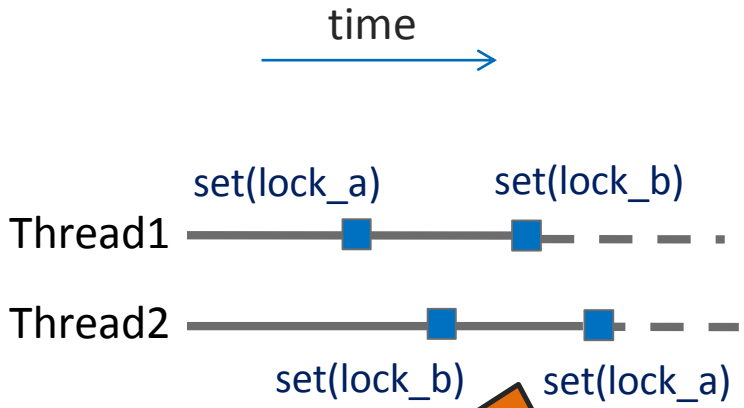
Threaded Applications (OpenMP)
Threaded Defects

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

Data race detection tools

Helgrind

- valgrind --tool=helgrind
- Many false alerts
  - Misses synchronization information
- Binary instrumentation during execution

Intel Inspector (XE?)

- They rename the tool every other year ☺
- Less false alerts
  - Especially for newer OpenMP clauses/constructs
- High runtime overhead for detailed analysis

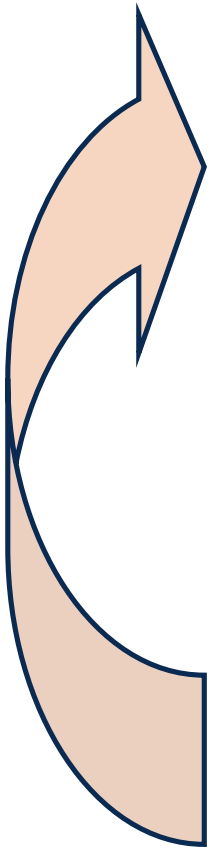
Data race detection tools
Archer

- 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

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)

Archer – Usage



- Compile the program with the –g and –fsanitize=thread 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

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)
```

```
$ cp -r ~lu23voz/tutorial/archer archer-examples
```

Hands On – Build for Archer

- Go into the NPB directory
- Edit config/make.def or copy archer.def from examples
- Disable any other tool (i.e. use mpifc, unset PREP)
- Use intel or gnu tool chain
- Build:

```
COMPFLAGS = -fopenmp –g –fsanitize=thread -march=knl \
            -mtune=knl -ffast-math
…

MPIF77 = mpifc

…

FLINK   = mpigcc
```

```
$ module use ~lu23voz/.modules
$ module load clang
$ cp -r ~lu23voz/tutorial/archer archer-examples
```

Hands On - Prepare Job

- Create and edit the jobscript

```
$ cp -r ~lu23voz/tutorial/archer archer-examples
$ cd bin
$ cp ../archer-examples/archer.sbatch .
```

- Jobscript:

```
…
module use ~lu23voz/.modules
module load must/intel
…
export OMP_NUM_THREADS=6
CLASS=B
NPROCS=8
…
mpiexec $EXE
```

Hands On – Executing with Archer

```
$ module use ~lu23voz/.modules
$ module load clang
$ cp -r ~lu23voz/tutorial/archer archer-examples
```

- Submit the jobscript:

```
sbatch archer.sbatch
```

- Job output should read like:

```
…

NAS Parallel Benchmarks (NPB3.3-MZ-MPI) - BT-MZ MPI+OpenMP Benchmark
…
Total number of threads:     48  (  6.0 threads/process)
Calculated speedup =     47.97

Time step    1
…
Verification Successful
…
```

```
$ module use ~lu23voz/.modules
$ module load clang
$ cp -r ~lu23voz/tutorial/archer archer-examples
```

Hands-on

```
$ module load clang

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

or

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

or

```
$ gfortran –sanitize=thread -fopenmp –g –c prime_omp.f
$ clang –sanitize=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

Thank You