Data race detection for large OpenMP applications

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http://fpanalysistools.org/

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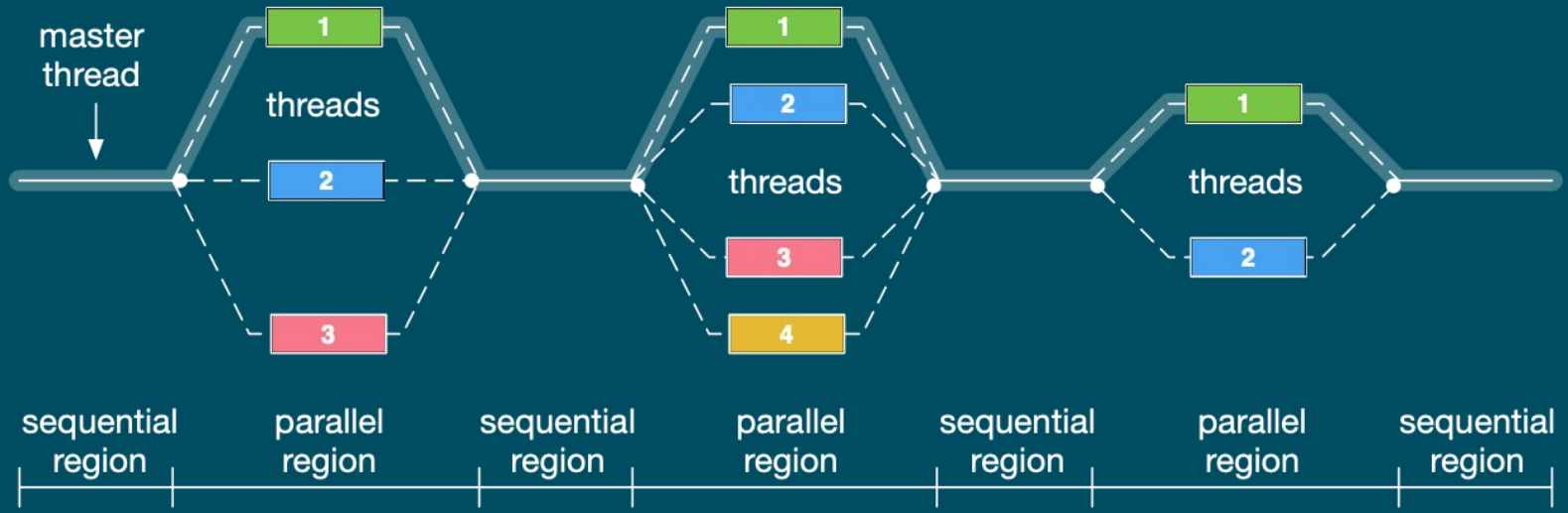
OpenMP

Enabling HPC since 1997

- Shared memory parallel programming
- Standard for on node parallelism in HPC

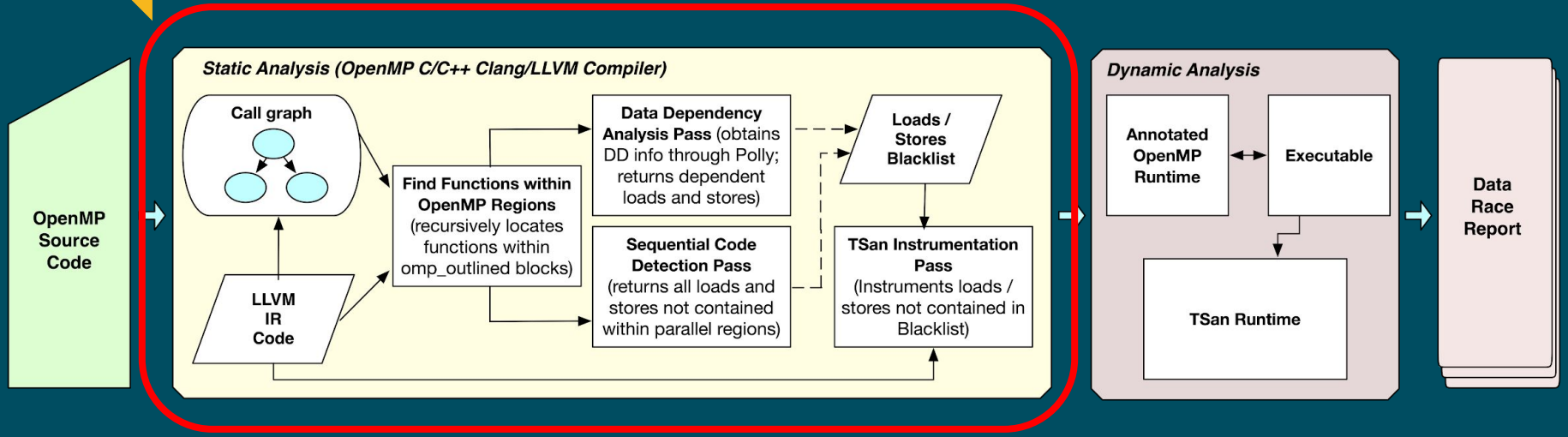


Data Race

Thread 1	Thread 2	Value of X
		0
local = X		0
local++		0
	Local = X	0
X = local		1
	local++	1
	X = local	1

- When shared data is accessed by two or more threads with no synchronization and at least one access is a write
- Leads to non deterministic behavior, crashes, and incorrect results
- Races are undefined behavior in C/C++
- Even “benign” races can be transformed by compilers into harmful races

Archer Tool Flow



Static Analysis

- Used to not instrument race free code
- Polly, an llvm polyhedral analysis
  - Used to exclude code with no data dependencies
- A custom llvm pass
  - Used to exclude serial code
  - Excludes loads/stores not reachable from OpenMP

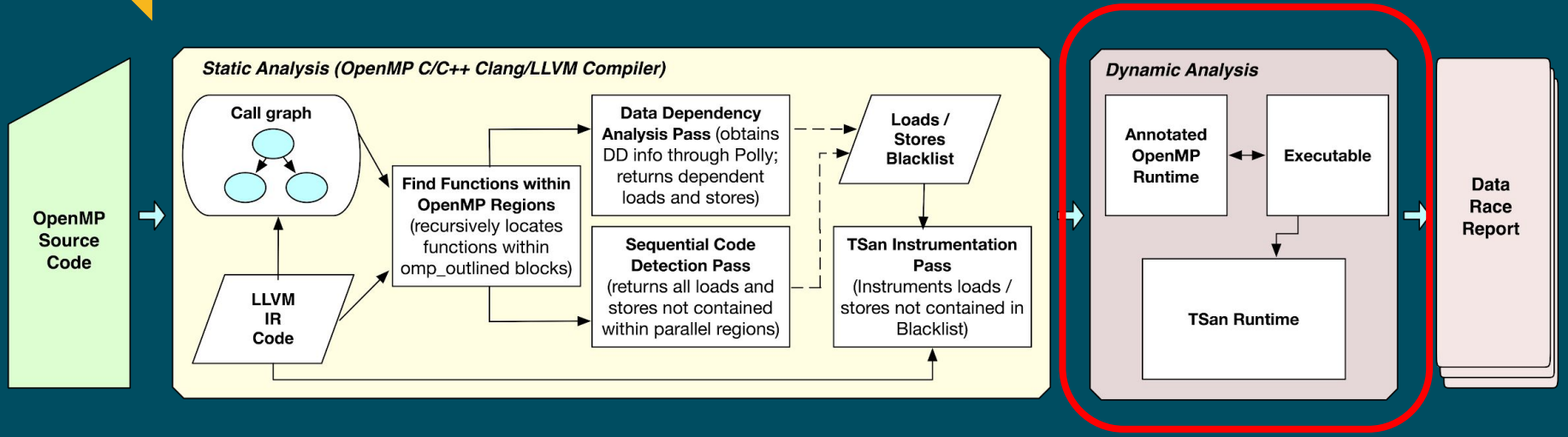
```
#pragma omp parallel for
  for (int i=0; i<N; i++) {
    a[i] = a[i] + 1;
  }
```

No data dependency code blacklisted

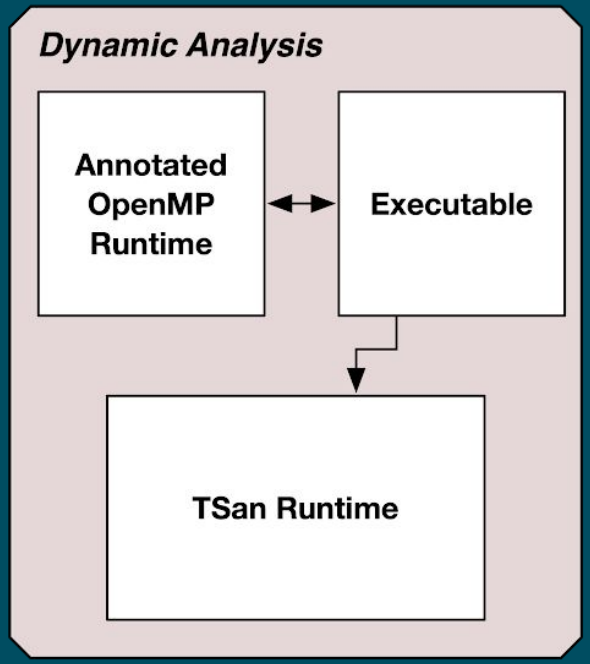
```
#pragma omp parallel for
  for (int i=0; i<N-1; i++) {
    a[i] = a[i+1];
  }
```

Potentially racy code instrumented

Archer Tool Flow



Dynamic Analysis



- ThreadSanitizer is used for dynamic analysis
  - Works well for Pthreads, but breaks on OpenMP constructs
- Annotated OpenMP runtime to highlight synchronization

Results

- AMG2013, algebraic multigrid solver for linear systems
  - Three unknown races found
- HYDRA, a simulator used at the National Ignition Facility
  - Found race which caused crashes when porting to Sequoia
  - First solution was to **disable** OpenMP
- Z-Pinch, a high-density physics code
  - Data race in macro extremely hard to pinpoint
  - Same value written in the same shared variable
  - IBM XL compiler transformations make the program crash

Examples

Exercise 1: Using Archer on an example from DataRaceBench

- OpenMP data race benchmark suite developed at LLNL
- Available at https://github.com/LLNL/dataracebench

Exercise 1

minusminus-orig-yes.c

```
57 const int len = 100;
58 int x[len];
59 int numNodes = len, numNodes2 = 0;
60
61 for (int i=0; i<len; i++) {
62   if (i%2 == 0) {
63     x[i] = 5;
64   } else {
65     x[i] = -5;
66   }
67 }
68
69 #pragma omp parallel for
70 for (int i=numNodes-1; i > -1; --i) {
71   if (x[i] <= 0) {
72     numNodes2-- ;
73   }
74 }
```

```
75
76 if (numNodes2 != -numNodes/2) {
77   printf ("numNodes2 = %d\n", numNodes2);
78   //printf ("A race occured\n");
79 } else {
80   //printf ("No race found\n");
81 }
```

Just because no race was found doesn't mean that there is no race! It just means that we were "lucky". Also these prints are only for illustration (not recommended) — **Sutter's "Pink Elephant" values!!**

Exercise 1 - ./step-01.sh

```
exercise-1 $ clang -g -fopenmp minusminus-orig-yes.c \
                  -o minusminus-without-archer
exercise-1 $ ./minusminus-without-archer
exercise-1 $ ./minusminus-without-archer
exercise-1 $ ./minusminus-without-archer
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exercise-1 $ ./minusminus-without-archer
exercise-1 $ ./minusminus-without-archer
exercise-1 $ ./minusminus-without-archer
[...]
```

Exercise 1 - ./step-02.sh

```
 exercise-1 $ clang-archer -g minusminus-orig-yes.c -o minusminus-with-archer
 exercise-1 $ ./minusminus-with-archer
==================
WARNING: ThreadSanitizer: data race (pid=29573)
  Write of size 4 at 0x7ffdab010858 by thread T1:
    #0 .omp_outlined._debug__
~/Module-Archer/excercise-1/minusminus-orig-yes.c:72:16
(minusminus-with-archer+0x4a7cb1)
    #1 .omp_outlined. ~/Module-Archer/excercise-1/minusminus-orig-yes.c:70:3
(minusminus-with-archer+0x4a7e02)
    #2 __kmp_invoke_microtask <null> (libomp.so+0x89cc2)

  Previous write of size 4 at 0x7ffdab010858 by main thread:
    #0 .omp_outlined._debug__
~/Module-Archer/excercise-1/minusminus-orig-yes.c:72:16
(minusminus-with-archer+0x4a7cb1)
    #1 .omp_outlined. ~/Module-Archer/excercise-1/minusminus-orig-yes.c:70:3
(minusminus-with-archer+0x4a7e02)
[...]
```

Exercise 1

minusminus-orig-yes.c

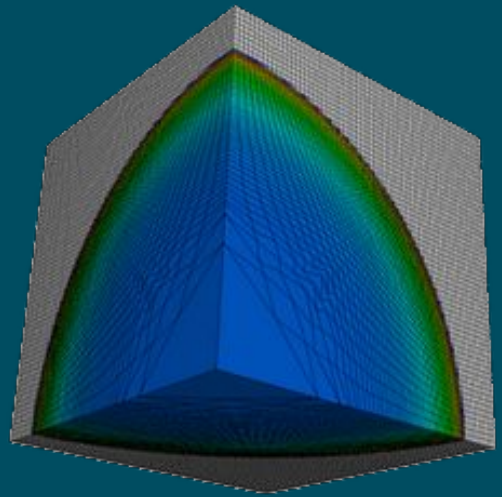
```
57 const int len = 100;
58 int x[len];
59 int numNodes = len, numNodes2 = 0;
60
61 for (int i=0; i<len; i++) {
62   if (i%2 == 0) {
63     x[i] = 5;
64   } else {
65     x[i] = -5;
66   }
67 }
68
69 #pragma omp parallel for
70 for (int i=numNodes-1; i > -1; --i) {
71   if (x[i] <= 0) {
72     numNodes2-- ;
73   }
74 }
```

```
75
76 if (numNodes2 != -numNodes/2) {
77   printf ("numNodes2 = %d\n", numNodes2);
78   //printf ("A race occured\n");
79 } else {
80   //printf ("No race found\n");
81 }

// Again the prints are for illustration.
// Racy code has “catch-fire” semantics.
// So don’t rely upon printing after a race!
// Pink Elephant values!
```

Exercise 2 Application: LULESH

- Proxy application developed at LLNL
- Models a shock hydrodynamics problem



Exercise 2 - ./step-03.sh

```
exercise-2 $ mkdir build
exercise-2 $ cd build
exercise-2 $ cmake ../LULESH -DCMAKE_BUILD_TYPE=Release \
                             -DCMAKE_CXX_COMPILER=`which clang-archer++` \
                             -DWITH_MPI=Off \
                             -DWITH_OPENMP=On
-- The CXX compiler identification is Clang 8.0.1
-- Check for working CXX compiler:
/home/ibriggs/ARCHER/archer_install/bin/clang-archer++
-- Check for working CXX compiler:
/home/ibriggs/ARCHER/archer_install/bin/clang-archer++ -- works
-- Detecting CXX compiler ABI info
-- Detecting CXX compiler ABI info - done
-- Detecting CXX compile features
-- Detecting CXX compile features - done
-- Found OpenMP_CXX: -fopenmp=libomp (found version "3.1")
-- Found OpenMP: TRUE (found version "3.1")
[...]
```

Exercise 2 - ./step-03.sh

```
exercise-2 $ make
Scanning dependencies of target lulesh2.0
[ 16%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-comm.cc.o
[ 33%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-init.cc.o
[ 50%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-util.cc.o
[ 66%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-viz.cc.o
[ 83%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh.cc.o
[100%] Linking CXX executable lulesh2.0
[100%] Built target lulesh2.0
```

Exercise 2 - ./step-03.sh

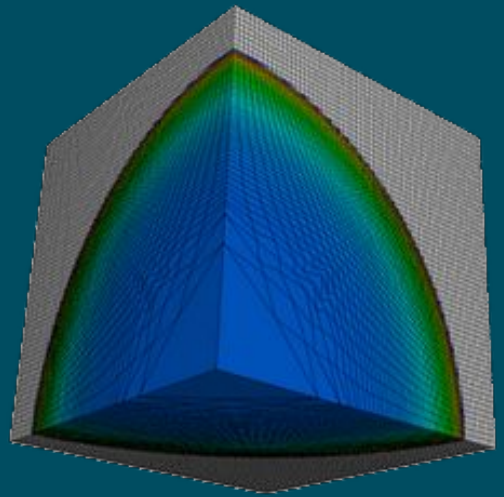
```
exercise-2 $ ./lulesh2.0
Running problem size 8^3 per domain until completion
Num processors: 1
Num threads: 3
Total number of elements: 512
[...]
Run completed:
   Problem size        =  8
   MPI tasks           =  1
   Iteration count     =  163
   Final Origin Energy =  1.788182e+04
   Testing Plane 0 of Energy Array on rank 0:
        MaxAbsDiff   = 1.136868e-12
        TotalAbsDiff = 1.120390e-11
        MaxRelDiff   = 5.521293e-14

Elapsed time         =        1.5 (s)
Grind time (us/z/c)  =  17.881075 (per dom)  (  1.492283 overall)
FOM                  =  55.925049 (z/s)
```

Exercise 3 Application: LULESH

- Proxy application developed at LLNL
- Models a shock hydrodynamics problem

Goal: find a race condition in a modified Lulesh



Exercise 3 - ./step-04.sh

```
exercise-3 $ mkdir build
exercise-3 $ cd build
exercise-3 $ cmake ../LULESH -DCMAKE_BUILD_TYPE=Release \
                             -DCMAKE_CXX_COMPILER=`which clang-archer++` \
                             -DWITH_MPI=Off \
                             -DWITH_OPENMP=On
-- The CXX compiler identification is Clang 8.0.1
-- Check for working CXX compiler:
/home/ibriggs/ARCHER/archer_install/bin/clang-archer++
-- Check for working CXX compiler:
/home/ibriggs/ARCHER/archer_install/bin/clang-archer++ -- works
-- Detecting CXX compiler ABI info
-- Detecting CXX compiler ABI info - done
-- Detecting CXX compile features
-- Detecting CXX compile features - done
-- Found OpenMP_CXX: -fopenmp=libomp (found version "3.1")
-- Found OpenMP: TRUE (found version "3.1")
[...]
```

Exercise 2 - ./step-04.sh

```
 exercise-3 $ make
Scanning dependencies of target lulesh2.0
[ 16%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-comm.cc.o
[ 33%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-init.cc.o
[ 50%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-util.cc.o
[ 66%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh-viz.cc.o
[ 83%] Building CXX object CMakeFiles/lulesh2.0.dir/lulesh.cc.o
[100%] Linking CXX executable lulesh2.0
[100%] Built target lulesh2.0
```

Exercise 3 - ./step-04.sh

```
 exercise-3 $ ./lulesh2.0
Running problem size 8^3 per domain until completion
[...]
==================
WARNING: ThreadSanitizer: data race (pid=28978)
  Write of size 8 at 0x7b880000e730 by thread T1:
    #0 .omp_outlined._debug__.33
~/Module-Archer/excercise-3/LULESH/lulesh.cc:983:37 (lulesh2.0+0x4c9eea)
    #1 .omp_outlined..34 ~/Module-Archer/excercise-3/LULESH/lulesh.cc:970
(lulesh2.0+0x4c9eea)
    #2 __kmp_invoke_microtask <null> (libomp.so+0x89cc2)

  Previous write of size 8 at 0x7b880000e730 by thread T2:
    #0 .omp_outlined._debug__.33
~/Module-Archer/excercise-3/LULESH/lulesh.cc:983:37 (lulesh2.0+0x4c9eea)
    #1 .omp_outlined..34 ~/Module-Archer/excercise-3/LULESH/lulesh.cc:970
(lulesh2.0+0x4c9eea)
    #2 __kmp_invoke_microtask <null> (libomp.so+0x89cc2)

[...]
```

Exercise 3

lulesh.c

```c
969 #pragma omp parallel for firstprivate(numNode)
970     for( Index_t gnode=0 ; gnode<numNode ; ++gnode )
971     {
972        Index_t count = domain.nodeElemCount(gnode) ;
973        Index_t *cornerList = domain.nodeElemCornerList(gnode) ;
974        Real_t fx_tmp = Real_t(0.0) ;
975        Real_t fy_tmp = Real_t(0.0) ;
976        Real_t fz_tmp = Real_t(0.0) ;
977        for (Index_t i=0 ; i < count ; ++i) {
978           Index_t ielem = cornerList[i] ;
979           fx_tmp += fx_elem[ielem] ;
980           fy_tmp += fy_elem[ielem] ;
981           fz_tmp += fz_elem[ielem] ;
982        }
983        domain.fx(gnode + gnode%2) += fx_tmp ;
984        domain.fy(gnode) += fy_tmp ;
985        domain.fz(gnode) += fz_tmp ;
986     }
```

Thank You!

Questions?

pruners.github.io/archer