Comparing Intel Thread Checker and Sun Thread Analyzer

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Agenda

- Introduction

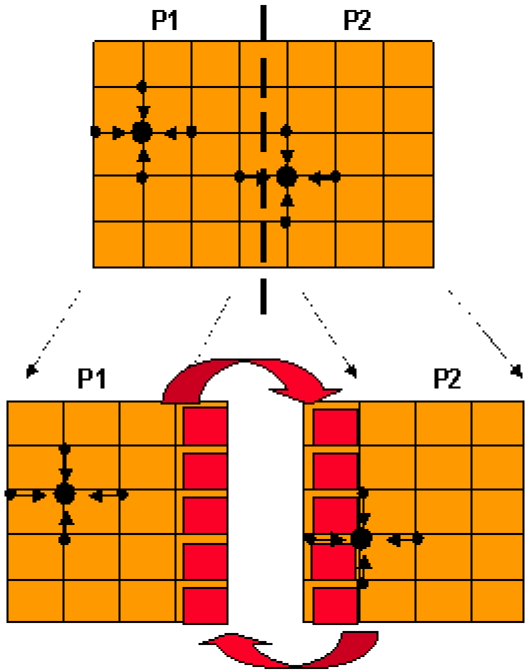
- Simple example walkthrough
  - Intel Thread Checker
  - Sun Thread Analyzer

- Further comparison
  - C++
  - Runtime & Memory consumption
  - Other features

- Conclusion

Introduction

- The fundamental difference between MPI and OpenMP:



- Shared-Memory (OpenMP):
  - Data resides in shared address spaces of all threads

  → Danger of data races

- Distributed-Memory (MPI):
  - Data is (manually) distributed between all processes

  → Data has to be sent explicitly

- Virtually every multithreaded program we examined had at least one data race …

Data Race detection

- A data race occurs when all following conditions happen concurrently:
  - Two or more threads access the same memory location,
  - Between two synchronization points in an OpenMP program,
  - At least one thread modifies that location,
  - The accesses to the location are not protected, e.g. by locks.

- Principle design of a data race detection tool:
  - Instrument application
  - Trace memory references
  - Trace thread management operations } at runtime
  - Trace synchronization operations
  - Compare event pairs (two threads), check for possible data race

History

- Assure for Threads was first commercial product
    - OpenMP
    - Available on many plattforms

- 2000: Intel acquired KAI
    - Renamed the product to Intel Thread Checker
    - Available on Linux and Windows
    - On Intel-compatible architectures

- 2007: Sun Thread Analyzer
    - Available since Sun Studio 12
    - Available on Linux and Solaris
    - On Intel-compatible architectures and UltraSPARC architectures

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Example program

- C version of Jacobian solver from OpenMP website:

```
#pragma omp parallel private(i)
{
   [...]
   /* compute stencil, residual and update */
#pragma omp for
   for (j=1; j<m-1; j++)
     for (i=1; i<n-1; i++){
       resid =(ax * (UOLD(j,i-1) + UOLD(j,i+1))
                 + ay * (UOLD(j-1,i) + UOLD(j+1,i))
                 + b * UOLD(j,i) - F(j,i) ) / b;
       U(j,i) = UOLD(j,i) - omega * resid;
       error = error + resid*resid;
     }
} /* end of parallel region */
```

Parallel region

Worksharing

We deliberately introduced two parallelization mistakes related to the variables `resid` and `error`.

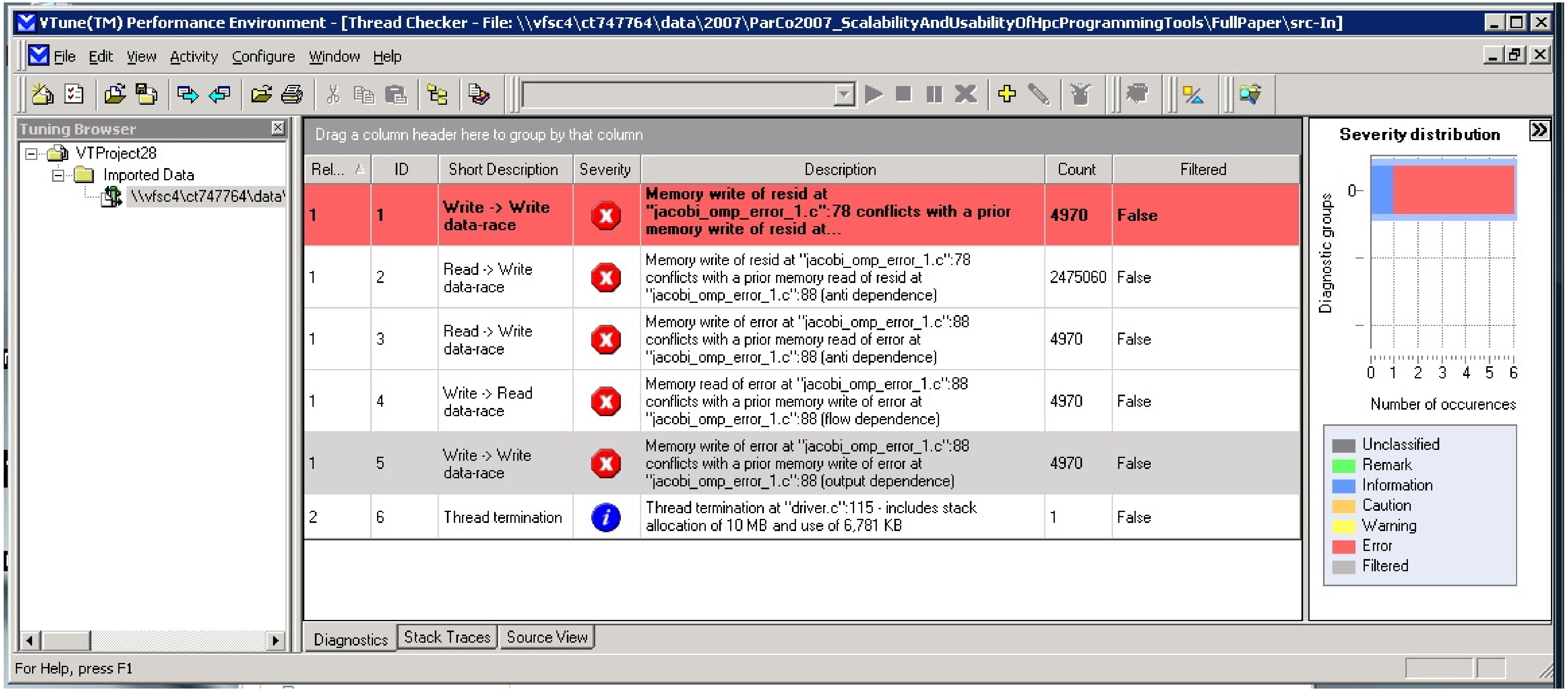
Expectations

- Correction:
  - Declare variable `resid` private
  - Declare variable `error` as reduction

- Why declaring `error` private would not be correct:
  - There would not be a data race! But …
  - **`error = error + resid*resid;`**
  - Contributions from all threads (`resid`) are accumulated
  - It is used in the sequential part later on → reduction

- Expectations (for the Jacobian solver):
  - Minimal: report data races in variables `resid` and `error`
  - Provide guides how to resolve the race conditions
  - Optimal: Propose to declare `error` as reduction

Intel Thread Checker



Rel...	ID	Short Description	Severity	Description	Count	Filtered
1	**1**	**Write -> Write data-race**	✖	**Memory write of resid at "jacobi_omp_error_1.c":78 conflicts with a prior memory write of resid at...**	**4970**	**False**
1	2	Read -> Write data-race	✖	Memory write of resid at "jacobi_omp_error_1.c":78 conflicts with a prior memory read of resid at "jacobi_omp_error_1.c":88 (anti dependence)	2475060	False
1	3	Read -> Write data-race	✖	Memory write of error at "jacobi_omp_error_1.c":88 conflicts with a prior memory read of error at "jacobi_omp_error_1.c":88 (anti dependence)	4970	False
1	4	Write -> Read data-race	✖	Memory read of error at "jacobi_omp_error_1.c":88 conflicts with a prior memory write of error at "jacobi_omp_error_1.c":88 (flow dependence)	4970	False
1	5	Write -> Write data-race	✖	Memory write of error at "jacobi_omp_error_1.c":88 conflicts with a prior memory write of error at "jacobi_omp_error_1.c":88 (output dependence)	4970	False
2	6	Thread termination	ℹ	Thread termination at "driver.c":115 - includes stack allocation of 10 MB and use of 6,781 KB	1	False

Intel Thread Checker

- Analysis results with binary instrumentation:
  - Allows checking of existing binary code (debug info helpful)
  - Program has to be executed with at least two threads
  - In total 10 errors for 3 different program locations
    - Unsynchronized write/write and read/write access to `resid`
    - Unsynchronized read from `resid` in write to `U[]`
    - Unsynchronized write/write and read/write access to `error`
    - Unsynchronized read from `resid` in write to `error`

- Together with the call stacks a correction proposal is given:
  - Protect access to variable `resid/error` by using either locks or critical regions
  - Make variable `resid/error` private by using either thread-local storage or private clauses

  → This is not correct in the case of `error`!

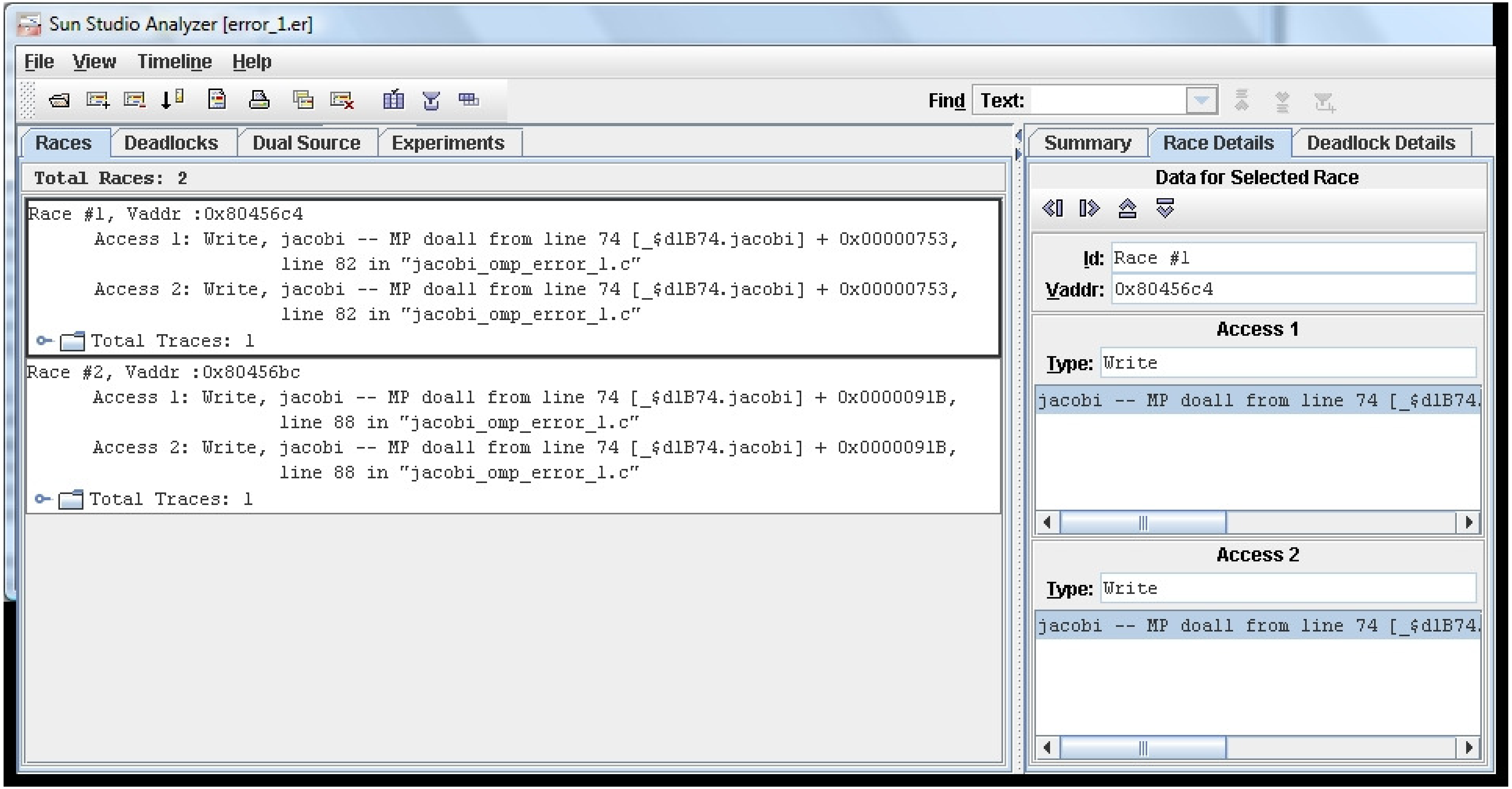
Intel Thread Checker

- Analysis results with source instrumentation:
  - Compilation with Intel Compilers required
  - Additional analysis capabilities for OpenMP programs – if program flow does not depend on the thread id
  - In total only 5 errors for 2 different program locations
  - The variable names `error` and `resid` are given

- The following correction proposal is given:
  - Protect access to variable `resid` by using either locks or critical regions
  - Make variable `error` private by using either thread-local storage or private clause
  - Consider declaring variable `error` as reduction

  → Declaring `error` as reduction is the optimal resolution!

Sun Thread Analyzer



```
Total Races: 2
Race #1, Vaddr :0x80456c4
      Access 1: Write, jacobi -- MP doall from line 74 [_$d1B74.jacobi] + 0x00000753,
                       line 82 in "jacobi_omp_error_1.c"
      Access 2: Write, jacobi -- MP doall from line 74 [_$d1B74.jacobi] + 0x00000753,
                       line 82 in "jacobi_omp_error_1.c"
      Total Traces: 1
Race #2, Vaddr :0x80456bc
      Access 1: Write, jacobi -- MP doall from line 74 [_$d1B74.jacobi] + 0x0000091B,
                       line 88 in "jacobi_omp_error_1.c"
      Access 2: Write, jacobi -- MP doall from line 74 [_$d1B74.jacobi] + 0x0000091B,
                       line 88 in "jacobi_omp_error_1.c"
      Total Traces: 1
```

Id: Race #1

Vaddr: 0x80456c4

Access 1

Type: Write

```
jacobi -- MP doall from line 74 [_$d1B74.
```

Access 2

Type: Write

```
jacobi -- MP doall from line 74 [_$d1B74.
```

Sun Thread Analyzer

- Analysis results:
  - In total 6 errors for 2 different program locations
    - A data race with read and write to variable `resid` is reported
    - A data race with read and write to variable `error` is reported

- Together with the call stacks a resolution proposal is given:
  - Protect access to variable `resid`/`error` by either using locks or critical regions

  → This is not correct in the case of `error`!

Guidance in the parallelization process

- In OpenMP the default is shared
- Finding all variables that have to be made private is
    - A lot of work
    - Error-prone

- Use your data race detection tool
    - Identify performance-critical hotspots
    - Insert e.g. OpenMP pragmas
    - Run the analysis with suited datasets
        - Use code coverage tool
    - Extract the list of variables with races
        - Most probably have to be made private / firstprivate / lastprivate
        - Thread Checker even proposes reduction variables

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Handling of C++ programs

- We tested a CG solver with external parallelization

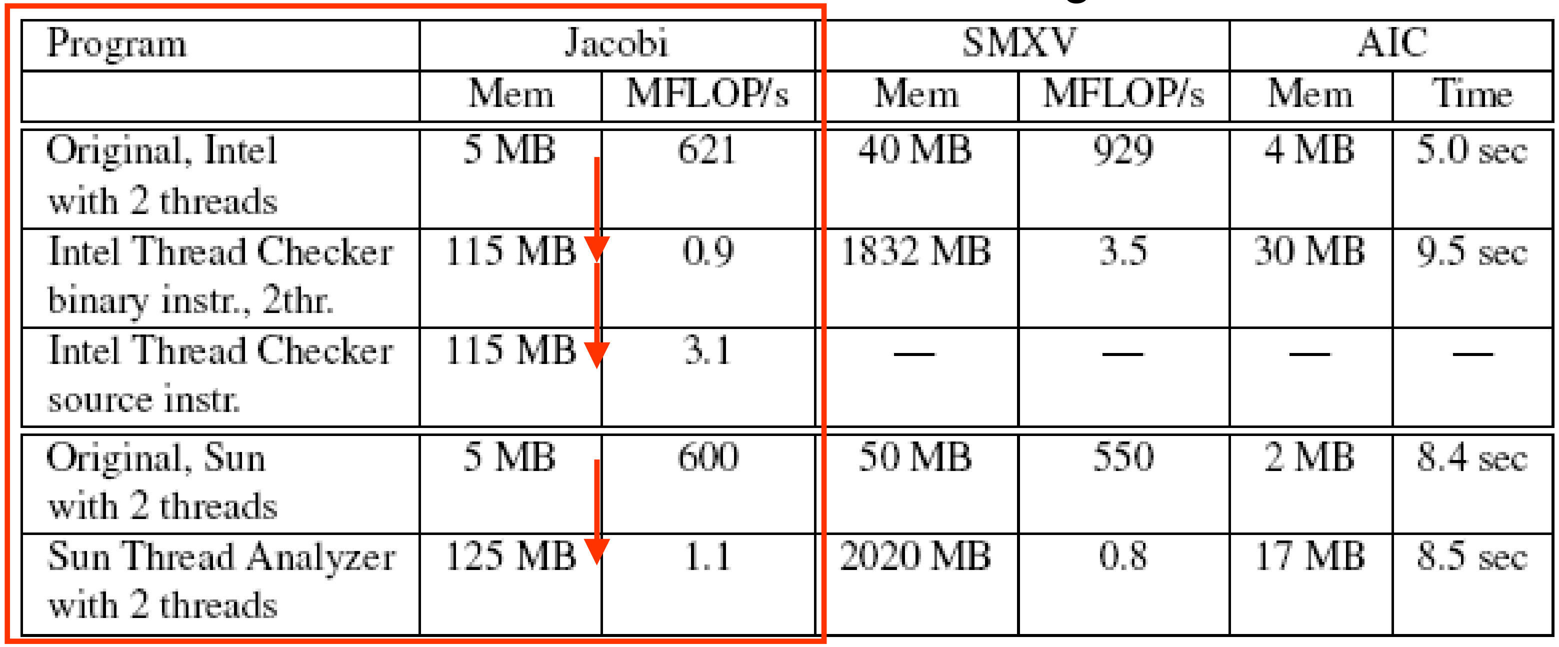
```
#pragma omp parallel firstprivate(iter, [...])
{
   while (iter < max_iter && sqrt(sigma) > tol)
   {    [...];    q = s + beta * q;    [...]    }
} // end omp parallel
```

  - The `operator*` member function contains orphaned OpenMP worksharing constructs

- Good news: The data races are reported where they occur!
- Not so good news: Additional races e.g. in the STL are reported

Runtime and Memory Consumption

- Advice is to use the smallest and still meaningful dataset



Program	Jacobi		SMXV		AIC	
	Mem	MFLOP/s	Mem	MFLOP/s	Mem	Time
Original, Intel with 2 threads	5 MB	621	40 MB	929	4 MB	5.0 sec
Intel Thread Checker binary instr., 2thr.	115 MB	0.9	1832 MB	3.5	30 MB	9.5 sec
Intel Thread Checker source instr.	115 MB	3.1	—	—	—	—
Original, Sun with 2 threads	5 MB	600	50 MB	550	2 MB	8.4 sec
Sun Thread Analyzer with 2 threads	125 MB	1.1	2020 MB	0.8	17 MB	8.5 sec

- Decrease grid resultion, limit the number of iterations, simulate just a few time steps, …
- Neverthless: Typical production datasets are impossible to analyze!
- The Sun tool still provides some scalability

Other features

- Re-using components (libraries) is good software engineering practice – but are these thread safe?
  - Bad performance advices from the past.

- Both tools provide deadlock detection capabilities:
  - Inappropriate use of mutex locks in Posix-Threads programs
  - Not an issue for OpenMP programs only using constructs
  - Can be enabled without data race detection capabilities, thus only little overhead is introduced

- If explicit memory flushes are used for implementing locks, no tool recognizes that
  - False positives are reported
  - Our advice: Do not use flushes for synchronization!

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Conclusion

- We recommend: Never put a multithreaded program into production before using one of these tools!
  - Both tools are capable of detecting data races in complex applications.

- Source instrumentation of Intel Thread Checker is advantageous for OpenMP programs – if applicable.
- Sun Thread Analyzer still offers scalability in analysis mode.

- Increased memory consumption may render both tools unusable.

End

Thank you for your attention.

Questions?