Runtime Correctness Checking Tools

Joachim Protze

Slides/Handson

```
% git clone
https://git.rwth-aachen.de/
protze/tools-tutorial.git
```

High Performance Computing

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- MUST reports
- MUST usage
- MUST features
- MUST future

Archer
- OpenMP data race detection
- Archer usage
- Archer GUI

Slides/Handson

```
% git clone
https://git.rwth-aachen.de/protze/tools-tutorial.git
```


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How many errors can you spot in this tiny example?

```c
#include <mpi.h>
#include <stdio.h>

int main (int argc, char** argv)
{
   int rank, size, buf[8];

   MPI_Comm_rank (MPI_COMM_WORLD, &rank);
   MPI_Comm_size (MPI_COMM_WORLD, &size);

   MPI_Datatype type;
   MPI_Type_contiguous (2, MPI_INTEGER, &type);

   MPI_Recv (buf, 2, MPI_INT, size - rank, 123, MPI_COMM_WORLD, MPI_STATUS_IGNORE);

   MPI_Send (buf, 2, type, size - rank, 123, MPI_COMM_WORLD);

   printf ("Hello, I am rank %d of %d.\n", rank, size);

   return 0;
}
```

No MPI_Init before first MPI-call
Fortran type in C
Recv-recv deadlock
Rank0: src=size (out of range)
Type not committed before use
Type not freed before end of main
Send 4 int, recv 2 int: truncation
No MPI_Finalize before end of main

Slides/Handson

```
% git clone https://git.rwth-aachen.de/protze/tools-tutorial.git
```

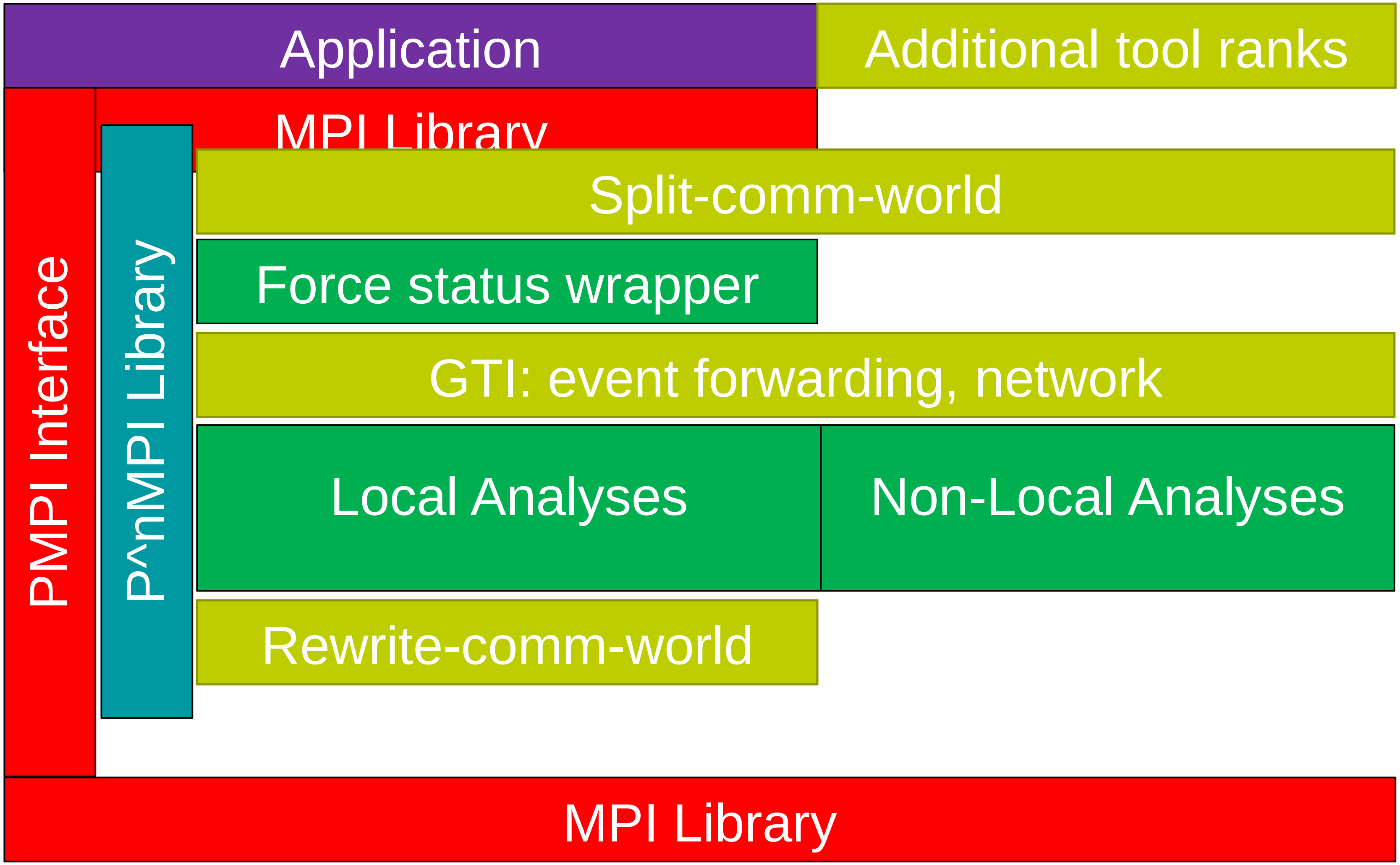
MPI usage errors

- MPI programming is error prone
- Bugs may manifest as:
  - Crashes
  - Hangs
  - Wrong results
  - Not at all! (Sleeping bugs)
- Tools help to detect these issues

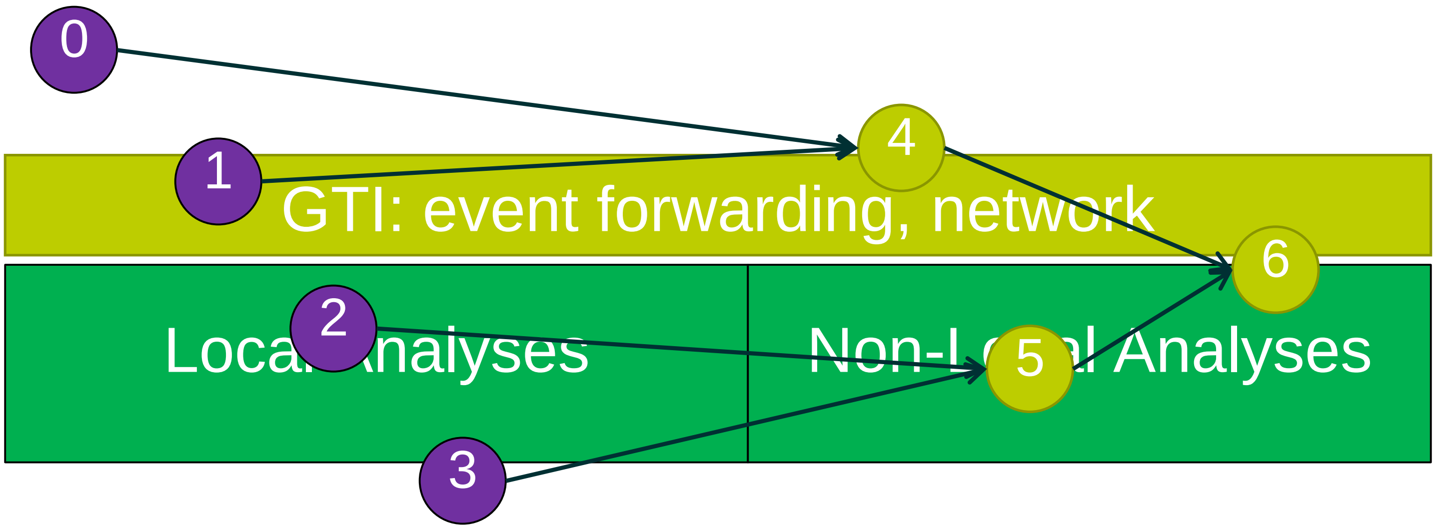
MPI usage errors

- Complications in MPI usage:
  - Non-blocking communication
  - Persistent communication
  - Complex collectives (e.g. Alltoallw)
  - Derived datatypes
  - Non-contiguous buffers
- Error Classes include:
  - Incorrect arguments
  - Resource errors
  - Buffer usage
  - Type matching
  - Deadlocks

MUST: Tool design



MUST: Tool design



MUST: Hands-on / Demo

- Load MUST

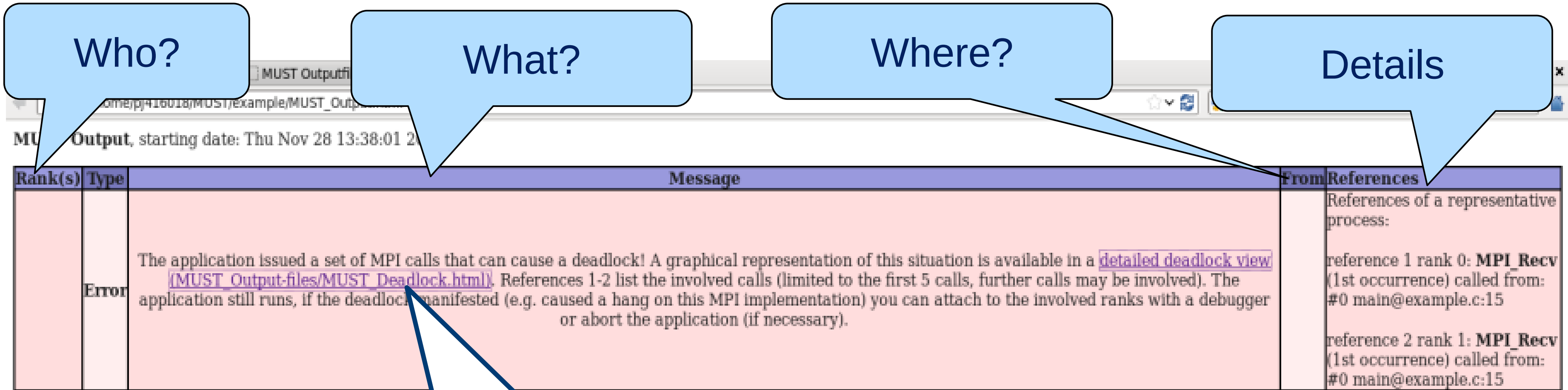
- Download the correctness examples:

```
% git clone https://git.rwth-aachen.de/protze/tools-tutorial.git
```

- Compile and execute the MPI example:

```
% mpicc -g must-example.c -o example.exe
% salloc -ppdebug
% mustrun --must:mpiexec srun -n4 -ppdebug ./example.exe
```

Must detects deadlocks

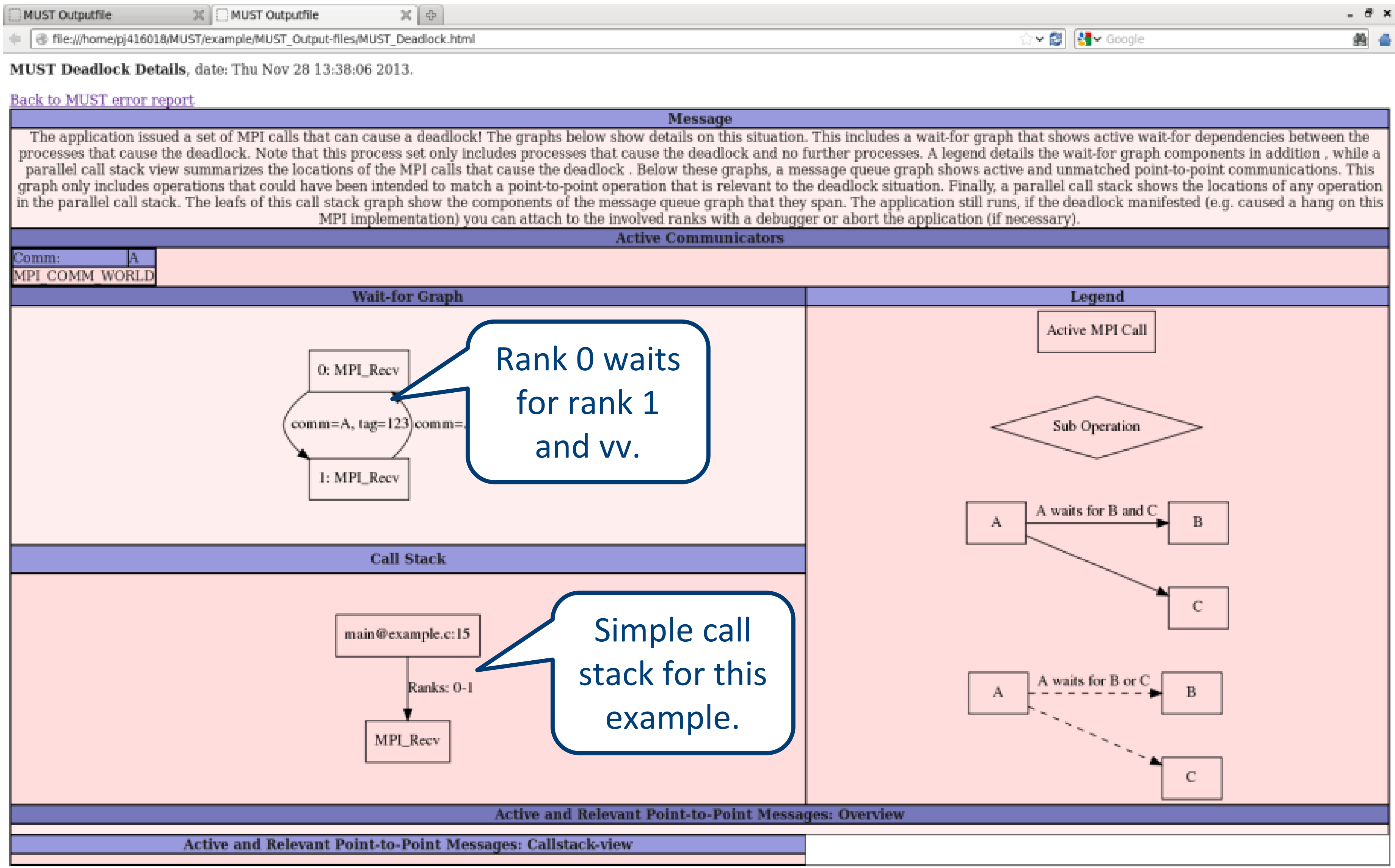


MU Output, starting date: Thu Nov 28 13:38:01 2

Rank(s)	Type	Message	From	References
	Error	The application issued a set of MPI calls that can cause a deadlock! A graphical representation of this situation is available in a detailed deadlock view (MUST_Output-files/MUST_Deadlock.html). References 1-2 list the involved calls (limited to the first 5 calls, further calls may be involved). The application still runs, if the deadlock manifested (e.g. caused a hang on this MPI implementation) you can attach to the involved ranks with a debugger or abort the application (if necessary).		References of a representative process: reference 1 rank 0: **MPI_Recv** (1st occurrence) called from: #0 main@example.c:15 reference 2 rank 1: **MPI_Recv** (1st occurrence) called from: #0 main@example.c:15

Click for graphical representation of the detected deadlock situation.

Graphical representation of deadlocks



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Sometimes fixing one defect introduces several new ones

```
#include <mpi.h>
#include <stdio.h>

int main (int argc, char** argv)
{
   int rank, size, buf[8];

   MPI_Init (&argc, &argv);
   MPI_Comm_rank (MPI_COMM_WORLD, &rank);
   MPI_Comm_size (MPI_COMM_WORLD, &size);

   MPI_Datatype type;
   MPI_Type_contiguous (2, MPI_INT, &type);
   MPI_Type_commit (&type);

   MPI_Request request;
   MPI_Irecv (buf, 2, MPI_INT, size - rank - 1, 123, MPI_COMM_WORLD, &request);

   MPI_Send (buf, 1, type, size - rank - 1, 123, MPI_COMM_WORLD);

   printf ("Hello, I am rank %d of %d.\n", rank, size);

   MPI_Finalize ();

   return 0;
}
```

Deadlock was fixed by non-blocking recv

MUST detects data races in asynchronous communication

Data race between send and ascynchronous receive operation

MUST Outputfile

file:///home/pj416018/MUST/example/MUST_Output.html

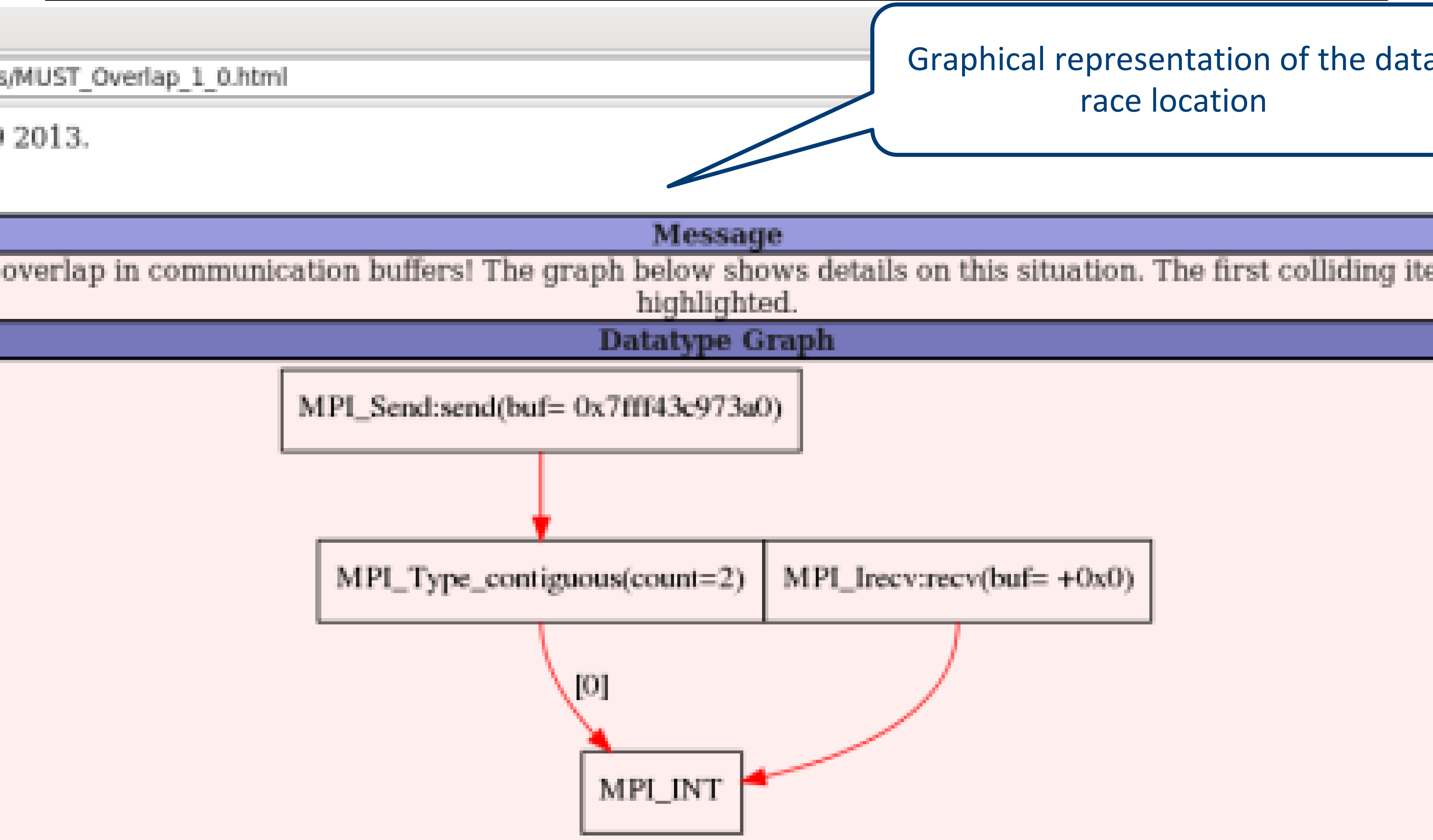
MUST Output, starting date: Mon Dec 2 18:36:19 2013.

Rank(s)	Type	Message		
1	Error	The memory regions to be transfered by this send operation overlap with regi nned by a pending non-blocking receive operation! (Information on the request associated with the other communication: Request activated at reference 1) (Information on the datatype associated with the other communication: MPI_INT) The other communication overlaps with this communication at position:(MPI_INT) (Information on the datatype associated with this communication: Datatype created at reference 2 is for C, commited at reference 3, based on the following type(s): { MPI_INT}) This communication overlaps with the other communication at position:(contiguous)[0](MPI_INT) A graphical representation of this situation is available in a [detailed overlap view (MUST_Output-files/MUST_Overlap_1_0.html)].	Representative location: **MPI_Send** (1st occurrence) called from: #0 main@example-fix4.c:19	References of a representative process: reference 1 rank 1: **MPI_Irecv** (1st occurrence) called from: #0 main@example-fix4.c:17 reference 2 rank 1: **MPI_Type_contiguous** (1st occurrence) called from: #0 main@example-fix4.c:13 reference 3 rank 1: **MPI_Type_commit** (1st occurrence) called from: #0 main@example-fix4.c:14
0-1	Error	There are 1 datatypes that are not freed when MPI_Finalize was issued, a quality application should free all MPI resources before calling MPI_Finalize. Listing information for these datatypes: -Datatype 1: Datatype created at reference 1 is for C, commited at reference 2, based on the following type(s): { MPI_INT}	Representative location: **MPI_Type_contiguous** (1st occurrence) called from: #0 main@example-fix4.c:13	References of a representative process: reference 1 rank 1: **MPI_Type_contiguous** (1st occurrence) called from: #0 main@example-fix4.c:13 reference 2 rank 1: **MPI_Type_commit** (1st occurrence) called from: #0 main@example-fix4.c:14
0-1	Error	There are 1 requests that are not freed when MPI_Finalize was issued, a quality application should free all MPI resources before calling MPI_Finalize. Listing information for these requests: -Request 1: Request activated at reference 1	Representative location: **MPI_Irecv** (1st occurrence) called from: #0 main@example-fix4.c:17	References of a representative process: reference 1 rank 1: **MPI_Irecv** (1st occurrence) called from: #0 main@example-fix4.c:17
0	Error	The memory regions to be transfered by this send operation overlap with regions spanned by a p non-blocking receive operation! (Information on the request associated with the other communication: Request activated at reference 1) (Information on the datatype associated with the other communication: MPI_INT) The other communication overlaps with this communication at position:(MPI_INT) (Information on the datatype associated with this communication: Datatype created at reference 2 is for C, commited at reference 3, based on the following type(s): MPI_INT}) This communication overlaps with the other communication at position:(contiguous)[0](MPI_INT) A graphical representation of this situation is available in a [detailed overlap view (MUST_Output-files/MUST_Overlap_0_0.html)].		References of a representative process: occurrence) called from: #0 main@example-fix4.c:14

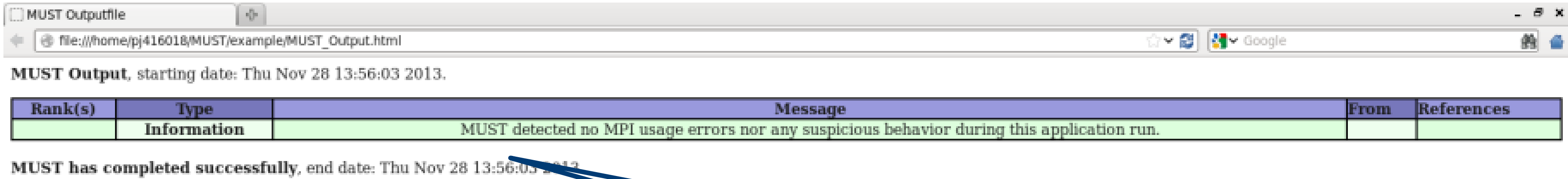
Missing MPI_Wait is diagnosed as resource leak.

Graphical representation of the race condition

Graphical representation of the data race location



MUST found no issue


MUST Outputfile

file:///home/pj416018/MUST/example/MUST_Output.html

MUST Output, starting date: Thu Nov 28 13:56:03 2013.

Rank(s)	Type	Message	From	References
	Information	MUST detected no MPI usage errors nor any suspicious behavior during this application run.		

MUST has completed successfully, end date: Thu Nov 28 13:56:03 2013.

No further error detected

Hopefully this message applies to many applications

MUST – Basic Usage

- Load MUST module/dotkit, e.g.:

```
% module load must
```

- Apply MUST with an mpiexec wrapper, that's it:
- Instead of

```
% $MPICC source.c –o exe
% $MPIRUN –np 4 ./exe
```

- Replace:

```
% $MPICC -g source.c –o exe
% mustrun --must:mpiexec $MPIRUN –np 4 ./exe
```

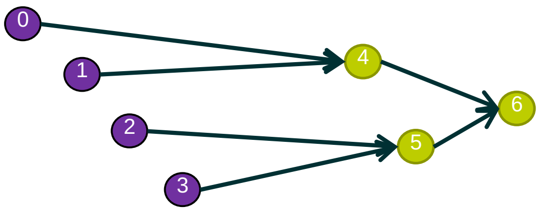
or:

```
% mustrun –np 4 ./exe
```

- After run: inspect "MUST_Output.html"

Remember the analysis tree?

- By default MUST uses a single extra node
- In batch: Allocate the extra process(es)!



- Query information about required processes:

```
% mustrun --must:info -np 4 ./exe
```

- For distributed analysis
  - Either:

```
% mustrun --must:distributed -np 4 ./exe
```

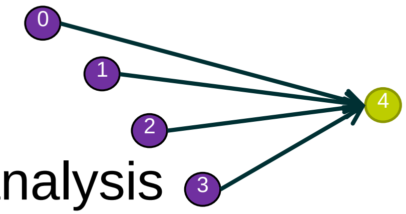
  - Or:

```
% mustrun --must:fanin 16 -np 4 ./exe
```

  - The latter allows you to specify a branching factor for the tree

Application crash handling

- Fatal error might stop the execution before report is written ☹



- Default: crash-safe centralized analyis
  – MPI call is only executed, when tool process finished analysis
  – Serializes MPI communication (overhead might be significant)
  – Assert that application does not crash (allows asynchronous analysis):

```
% mustrun --must:nocrash -np 4 ./exe
```

- Distributed: can handle crashes, but MPI might be dead
  – Use alternative communication layer for MUST:

```
% mustrun --must:nodesize 8 -np 4 ./exe
```

  – `nodesize` must be divider of processes scheduled per node
  – One process per `nodesize` becomes tool process
  – Might have some minor influence to the communication behavior

Analysis of multi-threaded MPI applications

- Default: MUST limits to `MPI_THREAD_FUNNELED`
  - Only the master thread can call MPI
  - The application must respect this thread-level
- Hybrid analysis: MUST requires `MPI_THREAD_MULTIPLE`
  - The application can use any MPI thread-level
  - MUST raises the requested thread-level to multiple

```
% mustrun --must:hybrid -np 4 ./exe
```

- MUST adds an analysis thread to each rank
  - ➢ Potentially oversubscribes the node? Should not matter for most apps.
- The additional tool processes are single-threaded
  - ➢ Does not fill those nodes, intelligent batch system might help in future?

Mustrun modes: Separate prepare and run

- Prepare MUST for execution with specific config (on frontend)

```
% mustrun --must:mode prepare -np 4 ./exe
```

- Execute with MUST in a batch job (after prepare):

```
% mustrun --must:mode run -np 4 ./exe
```

- Enforce new tool configuration/building and start execution:

```
% mustrun --must:mode preparerun -np 4 ./exe
```

Upcoming features based on LLVM/clang

- Data type checking

```
int array[10];
MPI_Send(array, MPI_FLOAT, 10, …);
```

  - Needs compile time information
  - Prototype implemented, needs to be integrated into release

- Data race detection

```
MPI_Isend(array, MPI_FLOAT, 10, …, &req);
array[5]++;
MPI_Wait(&req,…);
```

  - Integration of MUST and ThreadSanitizer/Archer

Installing MUST (→ Sysadmins)

- Configure with Cmake
  - Activate stack trace, if Dyninst is installed:
    - -DUSE_CALLPATH=on
    - -DSTACKWALKER_INSTALL_PREFIX=<dyninst-install-path>
  - Set a default mpiexec command:
    - -DMPIEXEC=srun
- Make / Install:
  - make -j16 install install-prebuilds

- Prebuilds are preconfigured tool configurations, that are installed with the tool
  - Runs **`--must:mode prepare`** for common tool configurations
  - Tool configuration not covered by the Prebuilds will trigger some tool configuration / compilation during “mustrun”

Archer: OpenMP data race detection

Data race detection tool: 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)
- Synchronization information based on OMPT
- More info: https://github.com/PRUNERS/archer
- Will hopefully be part of the 9.0 release of LLVM
  - Most probably missed the deadline ☹

Archer - Usage

- Compile the program with -g and -fsanitize=thread flag
  - `clang -g -fsanitize=thread -fopenmp 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.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.so)
```

Hands-on / Demo

- Load Archer module

```
$ cd ~/tools-tutorial/Debug-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 / Demo

- Compile with data race detection:

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

- Make Archer library available (could be done by module):

```
$ export OMP_TOOL_LIBRARIES=libarcher.so
```

- Execute with some threads:

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

Fix the issues, recompile, test again

Hands-on / Demo

- To verify that ARCHER is active, you can make ARCHER verbose:

```
$ ARCHER_OPTIONS="verbose=1" OMP_NUM_THREADS=2 ./a.out
Archer detected OpenMP application with TSan, supplying
OpenMP synchronization semantics
```

Usage for Fortran-code

- No Fortran compiler frontend with ThreadSanitizer in LLVM

- But we can use gfortran for compilation:

```
$ gfortran -fsanitize=thread -fopenmp -g -c app.f
```

- Still use clang for linking:

```
$ clang -fsanitize=thread -fopenmp -lgfortran app.o
$ OMP_NUM_THREADS=2 ./a.out
```

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

Advanced: use annotations for custom synchronization

OMP2012/371.applu331/src/syncs.f90:

```
      subroutine sync_left( ldmx, ldmy, ldmz, v )
…
      if (iam .gt. 0 .and. iam .le. mthreadnum) then
        neigh = iam - 1
        do while (isync(omp_get_thread_num() - 1) .eq. 0)
!$omp flush(isync)
        end do

        CALL AnnotateHappensAfter(__FILE__, __LINE__,
isync(omp_get_thread_num() - 1))
        CALL AnnotateHappensBefore(__FILE__, __LINE__,
isync(neigh))

        isync(neigh) = 0
!$omp flush(isync,v)
      endif
```

Upcoming: Archer GUI

- Implemented by LLNL summer student: Sam Thayer

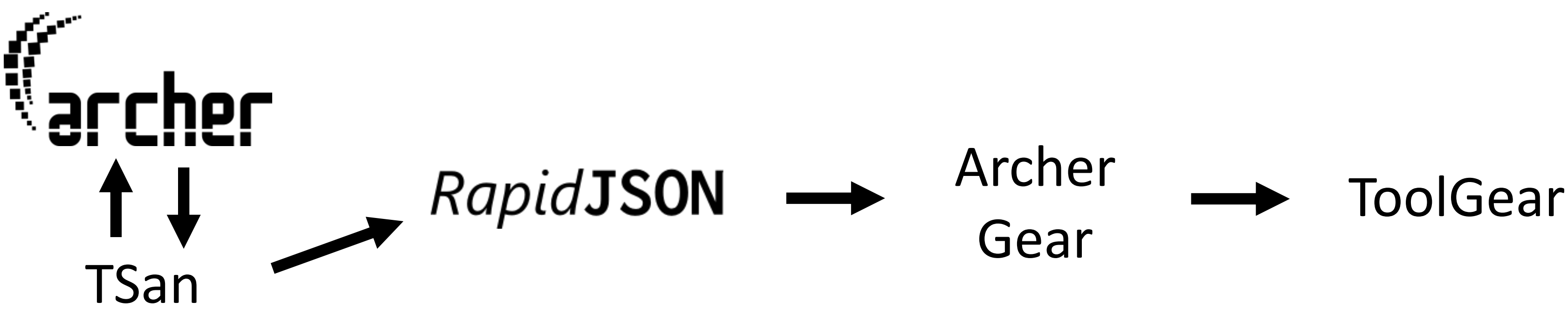
- Archer report is redirected into json output
- Aggregated report is presented in GUI

```
$ archer-gui <directory with Archer report files>
```

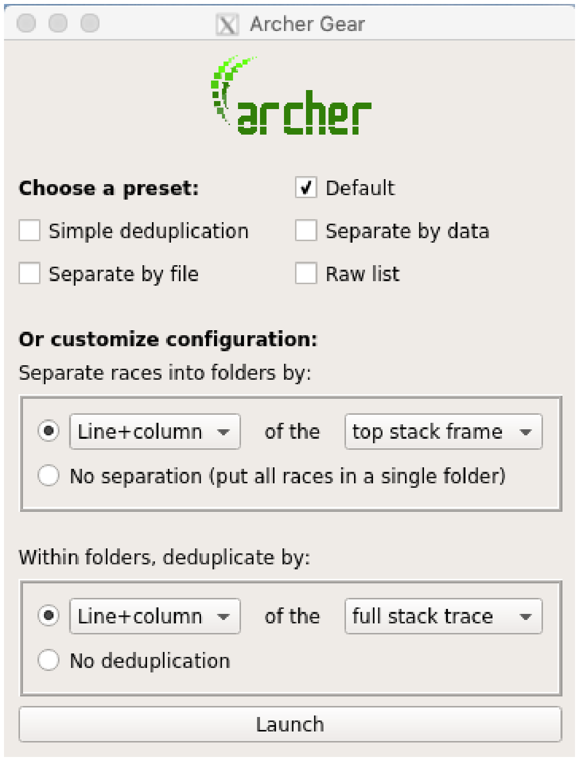
- Aggregates across threads and (MPI) processes

Upcoming: Archer GUI

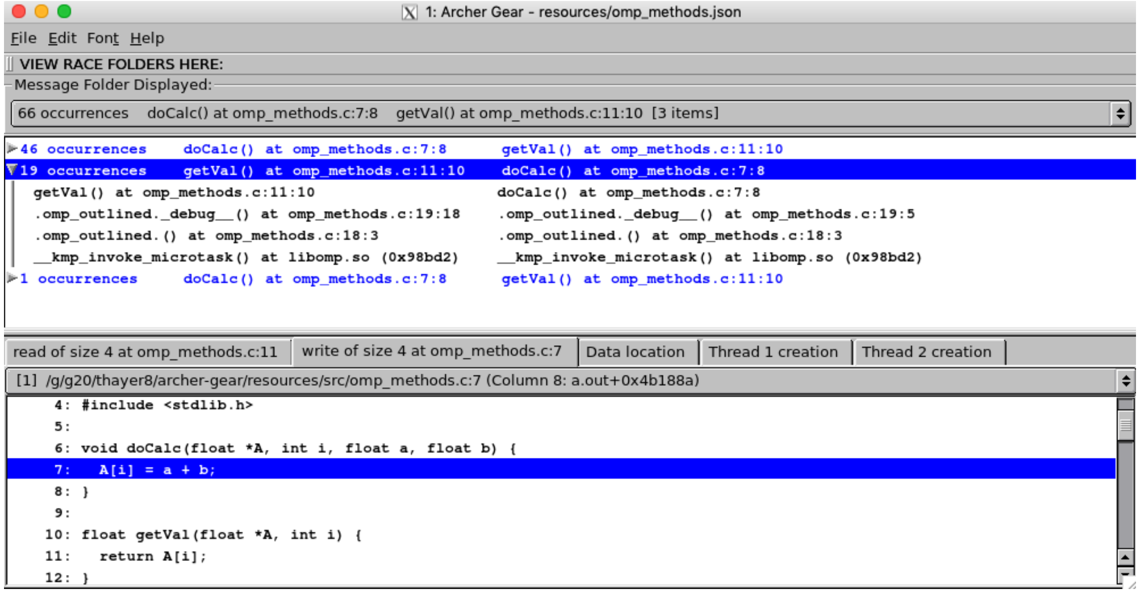
- Implemented by LLNL summer student: Sam Thayer
- Archer report is redirected to JSON output
- Aggregates reports into user-defined categories (across threads and MPI processes)
- Displays reports in ToolGear UI (implemented by LLNL employee John Gyllenhaal)
  – The same UI as other debugging tools such as MemCheckView



Upcoming: Archer GUI



- Offers simple options sufficient for most use cases
- Alternately, offers detailed control of report aggregation



Thank you for your attention.