MUST

MPI Runtime Error Detection Tool

Version 1.8.0

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Contents

1 Introduction

MUST detects usage errors of the Message Passing Interface (MPI) and reports them to the user. As MPI calls are complex and usage errors common, this functionality is extremely helpful for application developers that want to develop correct MPI applications. This includes errors that already manifest as segmentation faults or incorrect results, as well as many errors that are not visible to the application developer or do not manifest on a particular system or MPI implementation.

To detect errors, MUST intercepts the MPI calls issued by the target application and evaluates their arguments. The two main usage scenarios for MUST arise during application development and during porting. When a developer adds new MPI communication calls, MUST can detect newly introduced errors, especially also some that may not manifest in an application crash. Further, before porting an application to a new system, MUST can detect violations to the MPI standard that might manifest on the target system. MUST reports errors in a log file that can be investigated once the execution of the target executable finishes (irrespective of whether the application crashed or not).

2 Installation

The MUST software consists of three individual packages:

- P^nMPI
- GTI
- MUST

The P^nMPI package provides base infrastructure for the MUST software and intercepts MPI calls of the target application. GTI provides tool infrastructure, while the MUST package contains the actual correctness checks.

Starting with version 1.6, all three packages are contained in a single archive and configured and built at once.

Each MUST installation is built with a specific compiler and MPI library. It should only be used for applications built with the same compiler and MPI library. This is necessary as the behavior of MUST may differ depending on the MPI library. Compilers may be mixed if they are binary compatible.

Building MUST requires CMake for configuration. It is freely available at `http://www.cmake.org/`. You can execute *which cmake* to determine whether a CMake installation is available. If not, contact your system administrator or install a local version, which requires no root privileges. We suggest to use CMake version 3.9 or later (use *cmake --version*) for most functionality. Individual optional features may require even never CMake versions, which is specified in Section 2.1. From CMake version 3.20 on, full functionality is supported.

Further, to augment the MUST output with call stack information, which is very helpful for pinpointing errors, it is possible to utilize Backward or Dyninst. In that case, MUST uses either Backtrace-cpp or the Stackwalker API from Dyninst to read and print stack traces for errors. Section 7 presents the necessary steps for such an installation. Additionally, type-matching and data race analyses can be enabled by the integration of TypeART (see Section 8) and ThreadSanitizer (see Section 3.2), respectively.

MUST supports parallel build. Therefore you may want to append *–j<number of cores>* to the make calls.

2.1 Prerequisites to build and use MUST

- cmake (required 3.9 or newer, optional 3.20 or newer for TypeART, see *cmake --version*)
- python (required 3, see *python -V*)
- libxml2 with headers (libxml2-dev / libxml2-devel, required)
- graphviz (optional, to generate graphs)
- dyninst (optional, see Section 7.2)
- a browser (optional, to view html output)
- LLVM lit (optional 12 or newer to run tests, see *tests/README.md*)
- LLVM FileCheck (optional to run tests, see *tests/README.md*)
- LLVM-based compiler (optional 10 or newer for TypeART, see Section 8)
- MPI library, used by the application (required)

2.2 Configuring with CMake

All parts of MUST use CMake for configuration. CMake works best with 'out of source' builds, this is what we recommend in the installation steps below. Common CMake options include `-DCMAKE_INSTALL_PREFIX` to set the path to install into if you do not have root or to provide MUST as module environment package. CMake options can be configured with a GUI on many systems by using `ccmake` instead of cmake with all the -D flags listed below.

- When the ccmake gui appears:
- press c to generate options, press e to move on from any messages displayed by cmake.
- edit any options displayed,

- press c to see if there are any new options resulting from the previous round of choices
- repeat until you are happy with the options
- press g to generate the build
- move on to the make step as usual.

2.3 Building MUST

MUST can be built as follows (assuming GNU compilers):

```
tar xzf MUST-v1.8.0.tar.gz
cd MUST-v1.8.0
mkdir BUILD
cd BUILD
CC=$(which gcc) CXX=$(which gcc++) FC=$(which gfortran) \
cmake ../ \
     -DCMAKE_INSTALL_PREFIX=<MUST-INSTALLATION-DIR> \
     -DCMAKE_BUILD_TYPE=Release
make -j8 install
export PATH=<MUST-INSTALLATION-DIR>/bin:$PATH
```

In many cases, it is essential, to use the plain compilers for *CC*&Co, i.e., not the MPI compiler wrappers. The CMake call will determine your MPI installation in order to configure MUST correctly. If this should fail – or multiple MPIs are available – you can tip the configuration by specifying *–DMPI_C_COMPLIER=<FILE–PATH–TO–MPICC>* as well as *–DMPI_CXX_COMPLIER=<FILE–PATH–TO–MPICXX>* and *–DMPI_Fortran_COMPLIER=<FILE–PATH–TO–MPIF90>* as additional arguments to the *cmake* command. More advanced users can fine-tune the detection by specifying additional variables, consult the comments in *cmakemodules/FindMPI.cmake.* On clusters with special MPI environments, it helps to verify that *MPIEXEC* is set to the right mpiexec command (like srun).

Usually, no extra arguments are needed to configure MUST. You can specify -*DENABLE_TESTS=On* to activate the test suite that is included in MUST. Tests should only be started after installing MUST and can be run with from within the build directory with:

```
make check
```

or

```
lit tests
```

Some tests will fail even for a correct installation since they document future extensions. You can get a detailed test report for a single test with:

```
lit tests/<path/to/test/testname>
```

To run all *BasicChecks* with up to 4 tests in parallel:

```
lit -j4 tests/BasicChecks
```

More information on the test suite can be found in *<MUST–SOURCE–DIR>/tests/README.md*.

2.4 Install Prebuilt Configurations

To speed up the tool preparation time, we provide some prebuilt configurations for typical tool usage. These can be installed during building of MUST:

```
make -j8 install install-prebuilds
```

We strongly suggest this step for cluster installations. If prebuilts are not available, MUST will prepare an appropriate configuration during the execution of mustrun.

2.5 Environmentals

To work with MUST, it is sufficient to add *<MUST–INSTALLATION–DIR>/bin* to your *PATH* variable.

3 Usage

The following two steps allow you to use MUST:

- Replace the *mpiexec* command with *mustrun* to execute your application;
- Inspect the result file of the run.

3.1 Execution

The actual execution of an application with MUST is done by replacing the *mpiexec* command with *mustrun*. It performs a code generation step to adapt the MUST tool to your application and will run your application with MUST afterward.

The plain *mustrun* command that we use here is intended for small scale short-running applications and can exhibit very high runtime overhead. Section 5 presents further configurations of MUST that we tested with up to 16, 384 processes. The plain *mustrun* command uses all of MUST's correctness checks and a communication system where one MPI process is used to drive some of these checks. So when submitting a batch job, you should make sure to allocate resources for one additional task. Further, when calling *mustrun* you need to have access to the compilers and MPI utilities that were used to build MUST itself.

A regular *mpiexec* command like:

```
mpiexec -np 4 application.exe
```

Is replaced with:

```
mustrun -np 4 application.exe
```

It will execute your application with four tasks but requires one additional task, i.e. it will actually invoke *mpiexec* with *-np 5*.

For an example where the *mpiexec* command and the switch used to specify the number of processes is named differently:

```
srun -n 4 application.exe
```

You could use the following*mustrun* command:

```
mustrun --must:mpiexec srun --must:np -n  -n 4 application.exe
```

If your machine provides no compilers in batch jobs, you can prepare a run as follows:

```
mustrun --must:mode prepare -np 4 application.exe
```

In your batch job you would then just execute:

```
mustrun --must:mode run -np 4 application.exe
```

The *mustrun* tool provides further switches to modify its behavior, call *mustrun --must:help* for a summary. If you encounter errors during execution, please submit error reports where you use *--must:verbose* as an argument to *mustrun*.

It is not possible to pass arguments to mustrun that contain whitespace characters like spaces or tabs using command line switches. Use environment variables to pass such arguments to *mustrun* (see Section 3.1.1).

3.1.1 Passing arguments by environment variables

You can also use environment variables to pass switches to *mustrun*.

Every command line switch has a corresponding environment variable. These variables are named like the switches according to these rules:

- the two leading hyphens are removed
- all characters are converted to upper case
- colons and hyphens are replaced by underscores

For example the switch `--must:output-dir` can also be set with the environment variable `MUST_OUTPUT_DIR`.

Command line switches take precedence over environment variables. If both are used for the same switch, then the argument passed by the environment variable gets overridden by the command line argument.

Note the placement of quotes in the following example with whitespace in an MUST argument:

```
env "MUST_MPIEXEC=mpiexec --verbose" mustrun -np 4 application.exe
```

3.2 Execution of threaded applications

For support of threaded applications, MUST provides a thread-safe mode:

```
mustrun --must:hybrid -np 4 application.exe
```

Be aware that MUST lifts the required MPI threading level in this case to `MPI_THREAD_MULTIPLE`, while MUST limits the provided threading level without this flag to `MPI_THREAD_SINGLE`.

MUST additionally features checks to detect data races in hybrid programs with the help of ThreadSanitizer[1], which can be enabled by

```
mustrun --must:tsan -np 4 application.exe
```

This requires MUST to be configured with `-DENABLE_TSAN=On` (enabled by default) and the application under test to be compiled with `-fsanitize=thread` (supported by GNU- and LLVM-based compilers). Currently, ThreadSanitizer integration for data race detection was tested with the clang compiler from version 6 up to 13 and gcc version 9 to 12. The application also has to be linked with *<MUST-INSTALLATION-DIR>/lib/libonReportLoader.a* and built with debug info for MUST to generate meaningful reports for detected data races. Some linkers may not add unused symbols of the library to the application, in which case it helps to tell the linker to include all symbols from the library

```
$CC app.c -g \
    -Wl,--whole-archive install/must/lib/libonReportLoader.a \
    -Wl,--no-whole-archive \
    --fsanitize=thread
```

If MUST is configured with `-DENABLE_STACKTRACE=On` (enabled by default, see Section 7), information from the stacktraces will be used for reports on data races. To check whether MUST is configured properly with ThreadSanitizer support, run

```
lit tests/MpiTSan
```

or

```
make check-MpiTSan
```

For the tests however MUST has to be built with either gcc or clang in one of the aforementioned versions.

[1] `https://clang.llvm.org/docs/ThreadSanitizer.html`

3.3 Results

MUST stores its results in an HTML file named *MUST_Output.html*. It contains information on all detected issues, including information on where the error occurred. By default the *MUST_Output.html* file is placed in the execution directory. The output directory can be specified via *--must:output-dir <path>*.

Moreover, MUST's output can be split across multiple files by the user. To this end, the application under test may call `GTI_ChangeMessageFile(filename)`, which will result in MUST writing output to `filename`. This requires including the `GTI_Annotations.h` header and adding *<MUST–INSTALLATION–DIR>/include* to the include path for compilation. Note that the filename can be altered multiple times during execution. The filename is interpreted relative to MUST's main output directory.

3.3.1 Filtering Messages

MUST also allows its output to be filtered according to user-defined rules. Filter rules have the following general format: `messageType:MUST_ERROR_TYPE:source`, where `MUST_ERROR_TYPE` determines which type of errors or warnings to filter out (e.g., `MUST_ERROR_TYPEMATCH_MISMATCH`) and `source` is one of the following:

- specific file as `source`: `src:`*`filename.c`*
- specific function as `source`: `func:`*`function_name`*
- every `source`: `*`

For exmaple, the rule `messageType:MUST_WARNING_COMM_NULL:src:main.c` would filter out all of MUST warning regarding `MPI_COMM_NULL` or `NULL` as a communicator handle resulting from the source file `main.c`. The first two type of rules require MUST to use stacktraces, which can be enabled with the *--must:stacktrace* option (see Section 7).

Multiple filter rules may be specified in a file line by line and given to MUST via *--must:filter-file <file>*. Alternatively, the environment variable `MUST_FILTER_FILE` can be set to the file. For a list of more supported `MUST_ERROR_TYPES` see *<MUST–SOURCE–DIR>/modules/Common/MustEnums.h.*

4 Example

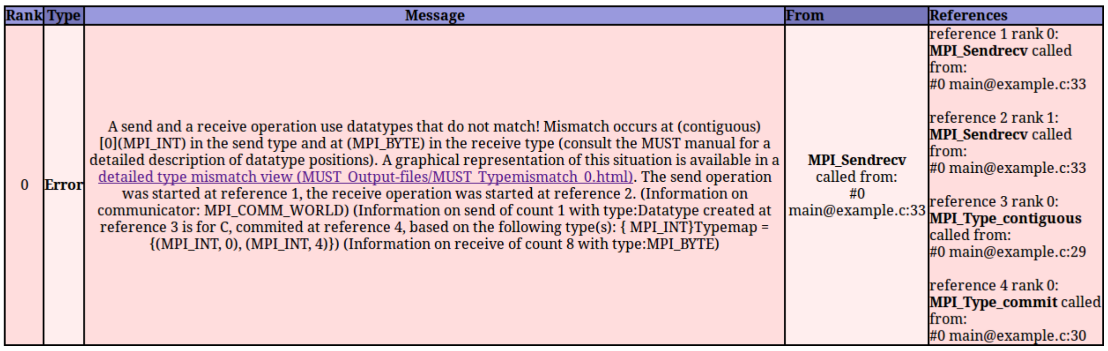
As an example consider the following application that contains three MPI usage errors:

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

int main (int argc, char** argv)
{
    int rank,
        size,
        sBuf[2] = {1,2},
        rBuf[2];
    MPI_Status status;
    MPI_Datatype newType;

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

    //Enough tasks ?
      if (size < 2)
      {
         printf ("This test needs at least 2 processes!\n");
         MPI_Finalize();
         return 1;
      }

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

      //1) Create a datatype
      MPI_Type_contiguous (2, MPI_INT, &newType);
      MPI_Type_commit (&newType);

      //2) Use MPI_Sendrecv to perform a ring communication
      MPI_Sendrecv (
              sBuf, 1, newType, (rank+1)%size, 123,
              rBuf, sizeof(int)*2, MPI_BYTE, (rank-1+size) % size, 123,
              MPI_COMM_WORLD, &status);

      //3) Use MPI_Send and MPI_Recv to perform a ring communication
      MPI_Send (sBuf, 1, newType, (rank+1)%size, 456, MPI_COMM_WORLD);
      MPI_Recv (rBuf, sizeof(int)*2, MPI_BYTE, (rank-1+size) % size, 456,
          MPI_COMM_WORLD, &status);

      //Say bye bye
      printf ("Signing off, rank %d.\n", rank);

    MPI_Finalize ();

    return 0;
}
/*EOF*/
```

4.1 Execution with MUST

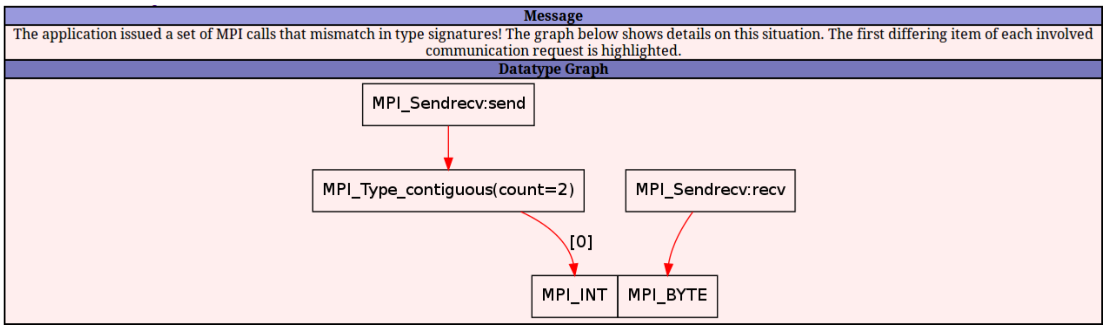
A user could set up the environment for MUST, build the application, and run it with the following commands:

```
#Set up environment
export PATH=<MUST-INSTALLATION-DIR>/bin:$PATH

#Compile and link, we rely on the ld-preload mechanism
mpicc example.c -o example.exe -g

#Run with four processes. We will need resources for five tasks!
mustrun -np 4 example.exe
```



Rank	Type	Message	From	References
0	Error	A send and a receive operation use datatypes that do not match! Mismatch occurs at (contiguous)[0](MPI_INT) in the send type and at (MPI_BYTE) in the receive type (consult the MUST manual for a detailed description of datatype positions). A graphical representation of this situation is available in a detailed type mismatch view (MUST_Output-files/MUST_Typemismatch_0.html). The send operation was started at reference 1, the receive operation was started at reference 2. (Information on communicator: MPI_COMM_WORLD) (Information on send of count 1 with type:Datatype created at reference 3 is for C, commited at reference 4, based on the following type(s): { MPI_INT}Typemap = {(MPI_INT, 0), (MPI_INT, 4)}) (Information on receive of count 8 with type:MPI_BYTE)	**MPI_Sendrecv** called from: #0 main@example.c:33	reference 1 rank 0: **MPI_Sendrecv** called from: #0 main@example.c:33 reference 2 rank 1: **MPI_Sendrecv** called from: #0 main@example.c:33 reference 3 rank 0: **MPI_Type_contiguous** called from: #0 main@example.c:29 reference 4 rank 0: **MPI_Type_commit** called from: #0 main@example.c:30

Figure 1: Type mismatch error report from MUST.



Message

The application issued a set of MPI calls that mismatch in type signatures! The graph below shows details on this situation. The first differing item of each involved communication request is highlighted.

Datatype Graph

Figure 2: Detail page for the type mismatch in Figure 5.

4.2 Output File

The output of the run with MUST will be stored in a file named *MUST_Output.html*. For this application MUST will detect three different errors that are:

- A type mismatch (Figure 1)
- A send-send deadlock (Figure 3)
- A leaked datatype (Figure 5)

Figure 1 shows the first error that MUST detects. The error results from the usage of non-matching datatypes, which are an `MPI_INT` and an `MPI_BYTE` of the same size as the integer value. This is not allowed according to the MPI standard. A correct application would use `MPI_INT` for both the send and receive call.

If MUST is configured with Dyninst (Section 7.2), the right column will list call stacks for all the involved MPI calls, as in Figure 5. Here the error is detected in the `MPI_Sendrecv` call in line 33.

The example shows the specification of the location in the datatype that causes the mismatch. The location `(CONTIGUOUS)[0](MPI_INT)` means that the used datatype is of contiguous kind. The mismatch is within the first element of the contiguous type, which is defined to be a base type, namely `MPI_INT`.

As another example `(VECTOR)[1][2](MPI_CHAR)` would address the third entry of the second block of a vector with base-type `MPI_CHAR`.

Figure 2 displays a graphical representation of the type mismatch. The image shows type trees of the involved data types. For a correct type match, both trees should share all their leaves. For a clearer view, matching leaves are hidden. The path to the first clash is highlighted in red. For derived types, the node labels display the count/blocklength value, used in the declaration of the type, while the edge label (corresponding to the path expression) gives the index of the block/blockitem, that leads to the first clash.

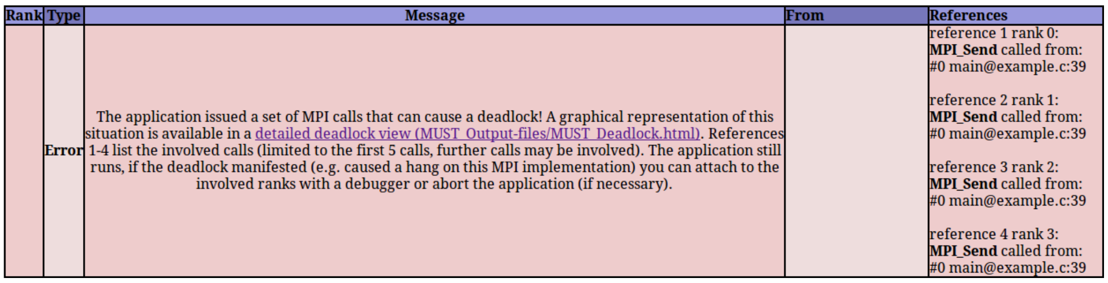
For communication buffers that access the same memory address concurrently ("buffer overlap"), similar descriptions and graphs are used. In this case, all nodes that point to distinct memory addresses are hidden, as the focus lies on the representation of the memory overlap.

The second error results from the application calling send calls that can lead to deadlock (Figure 3). Each task issues one call to `MPI_Send` while no matching receive is available. This can cause deadlock. However, as such calls would be buffered for most MPI implementations, this is a deadlock that only manifests for some message sizes or MPI implementations.

If MUST detects a deadlock, it provides visualization for its core, i.e., the set of MPI calls of which at least one call has to be modified or replaced. It stores a wait-for graph representation of this core in a file named *MUST_Deadlock.dot.* If available, MUST automatically translates this file into an image and provides a deadlock view (Figure 4), which shows the task dependencies and a parallel call stack. This graph file uses the DOT language of the *Graphviz* package. If a graphviz installation was available when MUST was installed, it automatically visualizes the graph. Otherwise, you can visualize it by issuing *dot -Tps MUST_Deadlock.dot -o deadlock.ps* after installing this tool. You can open the file *deadlock.ps* with the postscript viewer of your choice (DOT also supports additional output formats). If MUST was configured with Dyninst (Section 7.2), it will also print a parallel call stack in a file called *MUST_DeadlockCallStack.dot*, which Figure 4 shows at the bottom. This stack includes any MPI call that was referred to in the wait-for graph. Especially if processes use non-blocking communications, this call stack may include multiple MPI calls for each process.

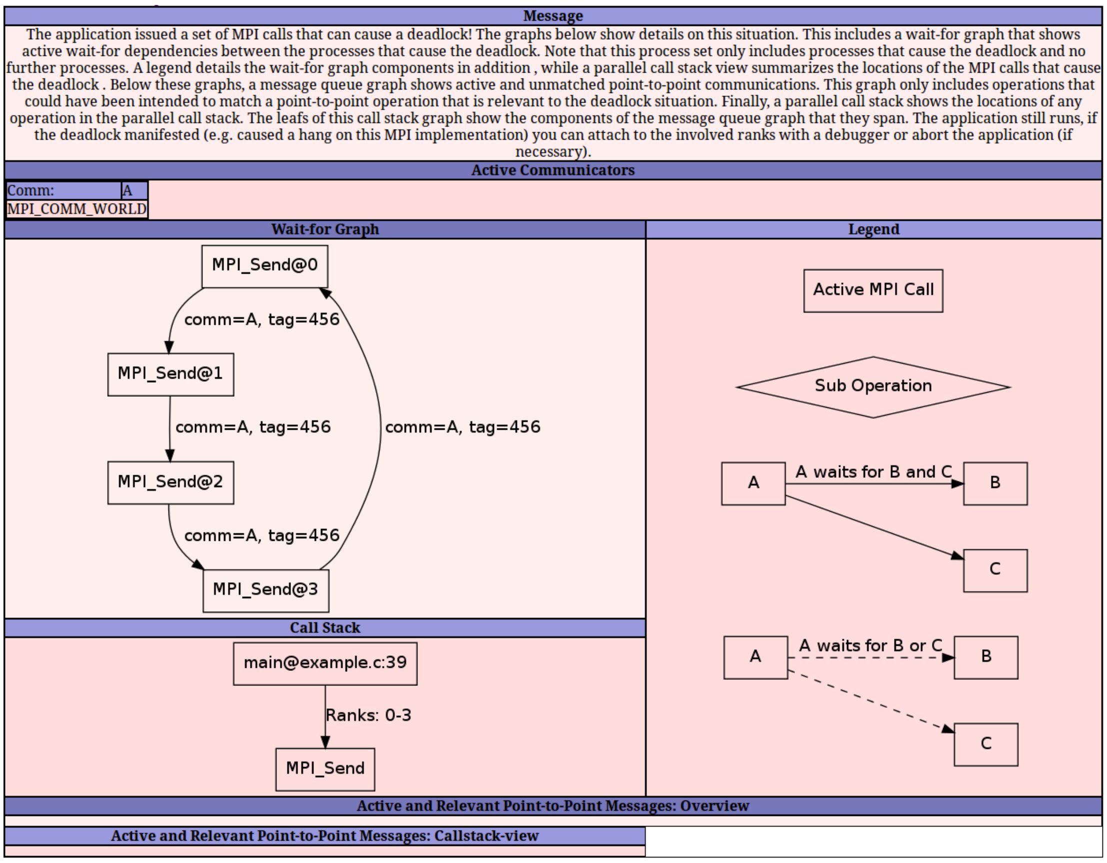
Further graphs in the deadlock view show information about the message matching state to highlight any call that might have been intended to match a blocked point-to-point call. Since no outstanding point-to-point message exists in the deadlock situation of Figure 3, these graphs are empty.

Finally, MUST detects that the application leaks MPI resources when calling `MPI_Finalize`. In particular, this is a datatype created with an `MPI_contiguous` call. Applications should free all such resources before invoking `MPI_Finalize`, as harmful leaks are easier to detect in such cases.



Rank	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 1-4 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).		reference 1 rank 0: **MPI_Send** called from: #0 main@example.c:39 reference 2 rank 1: **MPI_Send** called from: #0 main@example.c:39 reference 3 rank 2: **MPI_Send** called from: #0 main@example.c:39 reference 4 rank 3: **MPI_Send** called from: #0 main@example.c:39

Figure 3: Send-send deadlock report from MUST, basic report.



Message

The application issued a set of MPI calls that can cause a deadlock! The graphs below show details on this situation. This includes a wait-for graph that shows active wait-for dependencies between the processes that cause the deadlock. Note that this process set only includes processes that cause the deadlock and no further processes. A legend details the wait-for graph components in addition , while a parallel call stack view summarizes the locations of the MPI calls that cause the deadlock . Below these graphs, a message queue graph shows active and unmatched point-to-point communications. This graph only includes operations that could have been intended to match a point-to-point operation that is relevant to the deadlock situation. Finally, a parallel call stack shows the locations of any operation in the parallel call stack. The leafs of this call stack graph show the components of the message queue graph that they span. 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).

Active Communicators

Comm:	A
MPI_COMM_WORLD	

Wait-for Graph

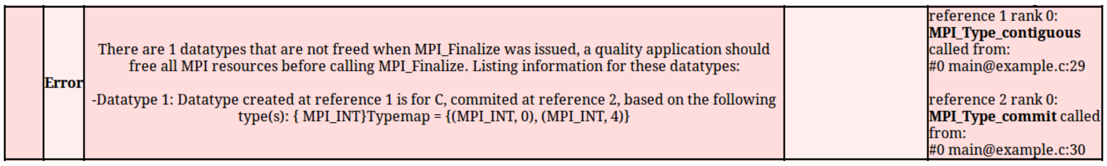
Legend

Call Stack

Active and Relevant Point-to-Point Messages: Overview

Active and Relevant Point-to-Point Messages: Callstack-view

Figure 4: Deadlock view for the send-send deadlock.



	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}Typemap = {(MPI_INT, 0), (MPI_INT, 4)}		reference 1 rank 0: **MPI_Type_contiguous** called from: #0 main@example.c:29 reference 2 rank 0: **MPI_Type_commit** called from: #0 main@example.c:30

Figure 5: Resource leak report from MUST.

5 MUST's Operation Modes

MUST's analysis of all MPI calls causes runtime overhead. As a result, it is important to adapt its configuration such that its overhead stays acceptable. While its default configuration (*mustrun* without additional switches) is easy to use, more advanced configurations may be required. MUST's overhead primarily results from:

- Correctness checks that require information from multiple processes, and
- A communication mode that allows MUST to detect MPI usage errors even if the application crashes.

MUST can use more than one additional process to run expensive correctness checks, while a shared memory based communication mode allows MUST to tolerate application crashes with limited runtime overhead.

5.1 Mode Overview

MUST provides the following operation modes that adapt its overhead to the target use-case:

1. **(Default) Very slow, Centralized, application may crash:**
   - Command line: *mustrun -np X exe*
   - One extra process for correctness checking
   - All checks enabled
   - Detects errors even if application crashes
   - Very slow, for short running tests at < 32 processes
2. **Fast, centralized, application does not crash:**
   - Command line: *mustrun -np X --must:nocrash exe*
   - One extra process for correctness checking
   - All checks enabled
   - Detects errors only if the application does not crash
   - Limited scalability, use for < 100 processes
3. **Fast, centralized, application may crash:**

- Command line: *mustrun -np X --must:nodesize Y exe*
- Number of extra processes: $1 + \lceil \frac{X}{Y-1} \rceil$
- All checks enabled
- Detects errors even if application crashs
- Limited scalability, use for < 100 processes
- Requires shared memory communication (Available on most linux based clusters)

4. **Distributed, application does not crash:**
   - Command line: *mustrun -np X --must:distributed [--must:fanin Z] exe*
   - Network of extra processes:
     - Layer 0: $A = \lceil \frac{X}{Z} \rceil$
     - Layer 1: $B = \lceil \frac{A}{Z} \rceil$
     - ...
     - Layer k: 1
   - If you need to reduce overheads, you can disable MUST's distributed deadlock detection with *--must:nodl*
   - Detects errors only if the application does not crash
   - Tested with $16,384$ processes

5. **Distributed, application may crash:**
   - Command line:
     mustrun -np X --must:distributed --must:nodesize Y [--must:fanin Z] exe
   - Network of extra processes:
     - Layer 0: $A = \lceil \frac{X}{Y-1} \rceil$
     - Layer 1: $B = \lceil \frac{A}{Z} \rceil$
     - Layer 2: $C = \lceil \frac{B}{Z} \rceil$
     - ...
     - Layer k: 1
   - If you need to reduce overheads, you can disable MUST's distributed deadlock detection with *--must:nodl*
   - Tested with $4,096$ processes
   - Requires shared memory communication (Available on most linux based clusters)

5.2 Mode Details

For any non-demanding (short and small scale) use case, we suggest operation Mode 1 (*mustrun -np X exe*), since it is always available and easy to use.

For more extensive application runs at moderate scale (< 100 processes) users should either use Mode 2 (*mustrun -np X --must:nocrash exe*) or Mode 3 (*mustrun -np X --must:nodesize Y exe*). While Mode 2 assumes that the application does not crash, Mode 3 uses a shared memory communication (Linux message queues) to tolerate application crashes. Besides the limited availability of this communication mechanism (most Linux-based systems), it requires more than one extra process to operate. The user needs to specify a node size Y that is a divisor of the number of cores available within each compute node. MUST then uses one tool process per $Y - 1$ application processes. It is important that the resource manager distributes MPI ranks in node-core order. That is, it fills each node completely and with successive ranks. The use of the *--must:fillnodes* switch to the *mustrun* command may help if the total number of MPI ranks does not fill all allocated nodes causing the resource manager to not fill nodes completely.

By adding the *--must:info* switch to any *mustrun* command, the user may retrieve additional information on the number of application tasks, tool tasks, and required nodes without running or preparing a MUST run. This provides valuable information to prepare batch job allocations.

Modes 4 (*mustrun -np X --must:distributed [--must:fanin Z] exe*) and 5 (*mustrun -np X --must:distributed --must:nodesize Y [--must:fanin Z] exe*) are intended for application runs at scale (> 100 processes, where we tested MUST with up to 16,384 processes). Both modes use a tree network to run several correctness checks, which increase their demand for extra computing cores. Again Mode 4 assumes that the application does not crash, while Mode 5 uses a shared memory communication to tolerate application crashes. Mode 5 comes with the same restrictions and allocation assumptions as Mode 3. For both modes, the user may specify the *--must:fanin Z* switch which controls the ratio of application to extra tool processes. The default value is 16, higher values may increase MUST's overhead, while lower values may reduce its overhead. Experience with MUST's distributed deadlock detection shows that it scales to an order of 16,384 processes but can double MUST's overhead. If MUST's overhead is too high for your use-case, you can add the switch *--must:nodl* to disable the distributed deadlock detection for Modes 4 and 5.

6 Included Checks

MUST currently provides correctness checks for the following classes of errors:

- Constants and integer values
- Communicator usage
- Datatype usage
- Group usage

- Operation usage
- Request usage
- Leak checks (MPI resources not freed before calling `MPI_Finalize`)
- Type mis-matches
- Overlapping buffers passed to MPI
- Deadlocks resulting from MPI calls
- Data races involving MPI calls

7 Stack trace information in MUST reports

MUST relies on external libraries to generate source code information included in MUST reports. The *--must:stacktrace* switch allows selecting the stack trace mechanism when launching mustrun. Since collecting stack traces can be costly and introduce significant runtime overhead, MUST will not collect stack traces by default. Therefore, the default of this setting is *none*. To enable stack traces based on backward-cpp, use *--must:stacktrace backward*. To enable stack traces based on Dyninst, use *--must:stacktrace dyninst*. The individual options will only be available if MUST was built with support for the individual stack trace library as described in the following. A single installation of MUST can be built with support for both stack trace libraries at the same time.

7.1 Recommended: MUST Installation with Backward-cpp

Since MUST version 1.8, MUST is configured with backward-cpp support enabled by default. To install MUST *without* backward-cpp support, the CMake variable **-DUSE_BACKWARD=Off** must be explicitly set during the configuration of MUST. Backward-cpp can work with different libraries to unwind the call stack[2] and to read the debug information from the binary[3]. The backward-cpp CMake configuration will automatically detect and select available debugging libraries.

7.2 Optional: MUST Installation with Dyninst

In order to install MUST with Dyninst support, a full Dyninst installation or a separate installation of the Dyninst Stackwalker API is needed. This usually requires an installation of libdwarf. Installation instructions for these can be found on the Dyninst website[4]. We tested the integration of dyninst in versions 7.0.1 and 8.0.1 and stackwalkerAPI in versions 2.1 and 8.0.1. For some systems, we identified issues for the older version of

[2]`https://github.com/bombela/backward-cpp/#libraries-to-unwind-the-stack`
[3]`https://github.com/bombela/backward-cpp/#libraries-to-read-the-debug-info`
[4]`https://www.dyninst.org/`

dyninst, that are listed in Section 9.2. We suggest to install libdwarf as a shared library (*--enable-shared* during its configure).

As Dyninst's build support is currently limited to GNU compilers, you should build your application and the tool with binary compatible compilers. To build dyninst with compilers other than GNU, make sure to set the variables *CC*, *CXX*, *GXX*, *LD* and *LINKER* for both the configure and the make step (this is not supported).

After a successful installation of the Stackwalker API it is necessary to configure MUST to use this installation. Use the following CMake variables:

- **-DUSE_CALLPATH=On** Enables the feature
- **-DSTACKWALKER_INSTALL_PREFIX=** Should point to the directory used for Stackwalker API installation (i.e. prefix given to its configure)
- **-DCALLPATH_STACKWALKER_EXTRA_LIBRARIES=** Additional libaries that are needed, if libdwarf was built statically, you will need to add an absolute file path to this lib here

Afterwards run *make* and *make install* to build and install MUST. When running MUST, no additional steps are needed. However, the stackwalker library will only be able to extract source file names and line numbers if the application was built with the debugging flag *-g*. Otherwise, it will list symbol addresses and library names instead.

Note that MUST expects that the shared libraries for libdwarf (if built as a shared library) and libelf are in the `LD_LIBRARY_PATH`.

8 TypeART Integration

MUST's native type mis-match detection focuses on distributed mis-matches, e.g., a send and a matching receive call using two incompatible data types. In order to additionally check for local type mis-matches, MUST provides optional integration of the type and memory allocation tracker TypeART[5].

8.1 MUST Preparation

By default, an existing and installed version of TypeART will be used for MUST. However, if TypeART is not installed at this system, the TypeART sources will be included as submodule and built from source. TypeART support requires an LLVM-based compiler in version 10 or newer and can be enabled during the configuration with **-DENABLE_TYPEART=On**. MUST will automatically detect and enable TypeART support if applicable during the configuration.

[5] `https://github.com/tudasc/TypeART`

8.2 Application Preparation

As TypeART relies on code instrumentation, its compiler wrapper needs to be used for compilation. For detailed information on requirements on and preparation of the application to test see *<MUST–SOURCE–DIR>/externals/typeart/README.md*. In case TypeART was built from source as a submodule, the needed wrappers can be found under *<MUST–INSTALLATION–DIR>/bin*, i.e, if you followed the suggetion in Section 2.5 the wrappers will be available without any other manual tweaking.

8.3 Execution

If MUST was configured with TypeART support and the application was built accordingly, MUST's TypeART checks can be enabled via the option *--must:typeart*. To check whether MUST is configured properly for TypeART checks, run

```
lit tests/TypeArt
```

or

```
make check-TypeArt
```

9 Troubleshooting

The following lists currently known problems or issues and potential workarounds.

9.1 Issues with Ld-Preload

In order to use MUST, your application must be linked against the core library of P^{n}MPI. Per default, MUST will add this library at execution time by using the ld-preload mechanism. If this causes issues, you can use the following command to manually link the P^{n}MPI library:

```
mpicc source.c -L<PNMPI-INSTALLATION-DIR>/lib  \
        -lpnmpi -o application.exe
```

Important: if you manually link against the MPI library, you must add the P^{n}MPI library first and the MPI library afterwards.

9.2 Issues with stackwalkerAPI

boost related error while build of MUST with dyninst-8:

```
error: boost/bar_foo.hpp: File not found
```

Solution for boost installation outside of /usr:
Edit *mustsrc/modules/Callpath/CMakeLists.txt* insert around line 21:

```
include_directories(/<BOOST_INSTALL_PREFIX>/include)
```

SEGFAULT on execution of *mustrun*:

```
rank 0 (of 4), pid 12345 catched signal nr 11
```

without any of the WARNINGs listed below. This issue affects almost every installation.

Solution:
Edit *src/dyninst/symtabAPI/src/Object-elf.C* around line 2069 and replace:

```
if(secNumber >= 1 && secNumber <= regions_.size()) {
```

by

```
if(secNumber >= 0 && secNumber < regions_.size()) {
```

... and rebuild / install dyninst

SEGFAULT on execution of *mustrun*:

```
rank 0 (of 4), pid 12345 catched signal nr 11
```

without any of the WARNINGs listed below and after fixing the issue above.

Solution:
Make sure that you use the same compiler family for building dyninst, P^{n}MPI, GTI, MUST and your application!

***mustrun* reports missing library:**

```
WARNING: Can't load module libcallpathModule.so (Error libdwarf.so:
cannot open shared object file: No such file or directory)
```

Solution:
Add *<LIBDWARF-INSTALLATION-DIR>/lib* to *LD_LIBRARY_PATH* (*libdwarf.so* should be located there).

10 Copyright and Contact

Contact *must-feedback@lists.rwth-aachen.de* for bug reports, feedback, and feature requests.