MPI Runtime Error Detection with MUST and Marmot

For the 8th VI-HPS Tuning Workshop

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Content

- MPI Usage Errors
- Error Classes
- Avoiding Errors
- Correctness Tools
- Runtime Error Detection
- MUST
- Marmot
- Hands On

MPI Usage Errors

- MPI programming is error prone
- Bugs may manifest as:
  - Crashes
  - Hangs
  - Wrong results
  - Not at all! (Sleeping bugs)
- Simple Example:

```
MPI_Type_contiguous (2, MPI_INT, &newtype);
MPI_Send (buf, count, newtype, target, tag, MPI_COMM_WORLD);
```

Error: Usage of un-comitted datatype

- Tools help to pin-point these bugs

MPI Usage Errors (2)

- 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

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Error Classes – Incorrect Arguments

- Complications
  - Calls with many arguments
  - In Fortran many arguments are of type INTEGER
  - Several restrictions for arguments of some calls

  ⇒ Compilers can’t detect all incorrect arguments
- Example:

```
MPI_Send(
      buf,
      count,
      MPI_INTEGER,
      target,
      tag,
      MPI_COMM_WORLD);
```

Error Classes – Resource Usage

- Complications
  - Many types of resources
  - Leaks
  - MPI internal limits
- Example:

```
MPI_Comm_dup (MPI_COMM_WORLD, &newComm);
MPI_Finalize ();
```

Error Classes – Buffer Usage

- Complications
  - Memory regions passed to MPI must not overlap (except send-send)
  - Derived datatypes can span non-contiguous regions
  - Collectives can both send and receive
- Example:

```
MPI_Isend (&(buf[0]), 5 /*count*/, MPI_INT, ...);
MPI_Irecv (&(buf[4]), 5 /*count*/, MPI_INT, ...);
```

Error Classes – Type Matching

- Complications
  - Complex derived types
  - Types match if the signature matches, not their constructors
  - Partial receives
- Example 1:

Task 0	Task 1
MPI_Send (buf, 1, MPI_INT);	MPI_Recv (buf, 1, MPI_INT);

  - Matches => Equal types match

Error Classes – Type Matching

- Example 2:
  - Consider type T1 = {MPI_INT, MPI_INT}

Task 0	Task 1
MPI_Send (buf, 1, T1);	MPI_Recv (buf, 2, MPI_INT);

  - Matches => type signatures are equal
- Example 3:
  - T1 = {MPI_INT, MPI_FLOAT}
  - T2 = {MPI_INT, MPI_INT}

MPI_Send (buf, 1, T1);	MPI_Recv (buf, 1, T2);

  - Missmatch => MPI_INT != MPI_FLOAT

Error Classes – Type Matching (3)

- Example 4:
  - T1 = {MPI_INT, MPI_FLOAT}
  - T2 = {MPI_INT, MPI_FLOAT, MPI_INT}

Task 0	Task 1
MPI_Send (buf, 1, T1);	MPI_Recv (buf, 1, T2);

  - Matches => MPI allows partial receives

- Example 4:
  - T1 = {MPI_INT, MPI_FLOAT}
  - T2 = {MPI_INT, MPI_FLOAT, MPI_INT}

Task 0	Task 1
MPI_Send (buf, 2, T1);	MPI_Recv (buf, 1, T2);

  - Missmatch => Partial send is not allowed

Error Classes – Deadlocks

- Complications:
  - Non-blocking communication
  - Complex completions (Wait{all, any, some})
  - Non-determinism (e.g. MPI_ANY_SOURC)
  - Choices for MPI implementation (e.g. buffered MPI_Send)
  - Deadlocks may be causes by non-trivial dependencies

- Example 1:

Task 0	Task 1
MPI_Recv (from:1);	MPI_Recv (from:0);

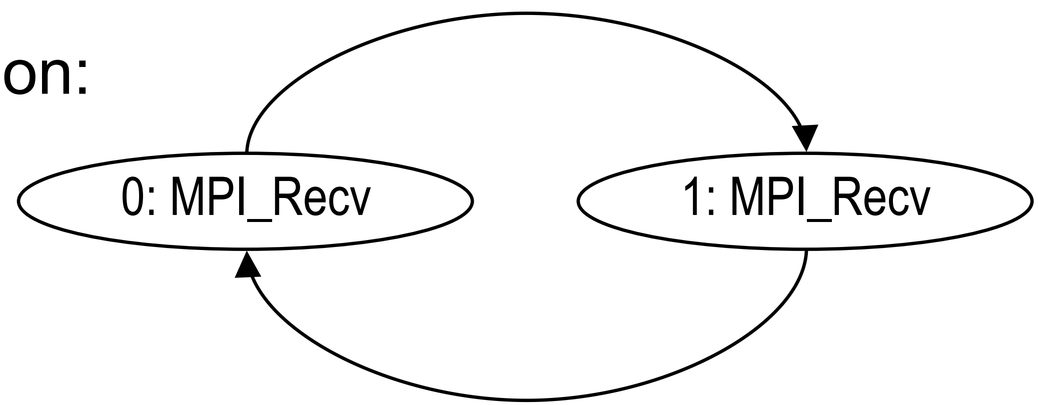
  - Deadlock: 0 waits for 1, which waits for 0

Error Classes – Deadlocks (2)

- How to visualise/understand deadlocks?
  - Common approach waiting-for graphs (WFGs)
  - One node for each rank
  - Rank X waits for rank Y => node X has an arc to node Y
- Consider situation from Example 1:

Task 0	Task 1
MPI_Recv (from:1);	MPI_Recv (from:0);

- Visualization:



- Deadlock criterion: cycle (For simple cases)

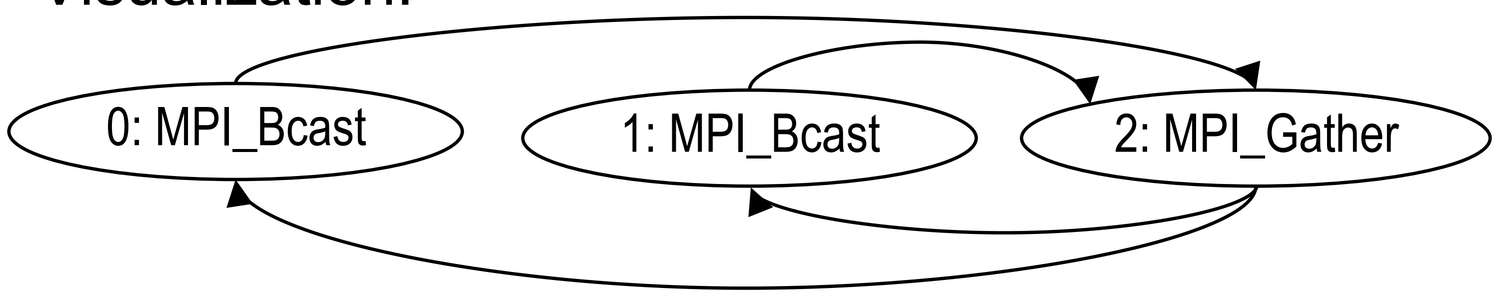
Error Classes – Deadlocks (3)

- What about collectives?
  - Rank calling collective waits for all tasks to issue a matching call

  ⇒ One arc to each task that did not call a matching call
  - One node potentially has multiple outgoing arcs
  - Multiple arcs means: waits for all of the nodes
- Example 2:

Task 0	Task 1	Task 2
MPI_Bcast (WORLD);	MPI_Bcast (WORLD);	MPI_Gather (WORLD);

- Visualization:



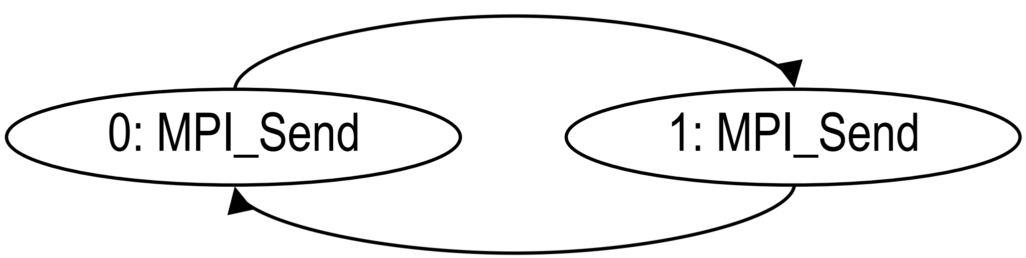
- Deadlock criterion: cycle (Also here)

Error Classes – Deadlocks (4)

- What about freedom in semantic?
  - Collectives may not be synchronizing
  - Standard mode send may (or may not) be buffered
- Example 3:

Task 0	Task 1
MPI_Send (to:1);	MPI_Send (to:0);

- This is a deadlock!
  - These are called “potential” deadlocks
  - Can manifest for some implementations and/or message sizes
- Visualization:



Error Classes – Deadlocks (5)

- What about timely interleaving?
  - Non-deterministic applications
  - Interleaving determines what calls match or are issued
  - Causes bugs that only occur "sometimes"
- Example 3:

Task 0	Task 1	Task 2
MPI_Send(to:1)	MPI_Recv(from:ANY); MPI_Recv(from:2)	MPI_Send(to:1)

- What happens:
  - Case A:
    - Recv (from:ANY) matches send from task 0
    - All calls complete
  - Case B:
    - Recv (from:ANY) matches send from task 1
    - Tasks 1 and 0 deadlock

Error Classes – Deadlocks (6)

- What about "any" and "some"?
  - MPI_Waitany/Waitsome and wild-card (MPI_ANY_SOURCE) receives have special semantics
  - These wait for at least one out of a set or ranks
  - This is different from the "waits for all" semantic
- Example 4:

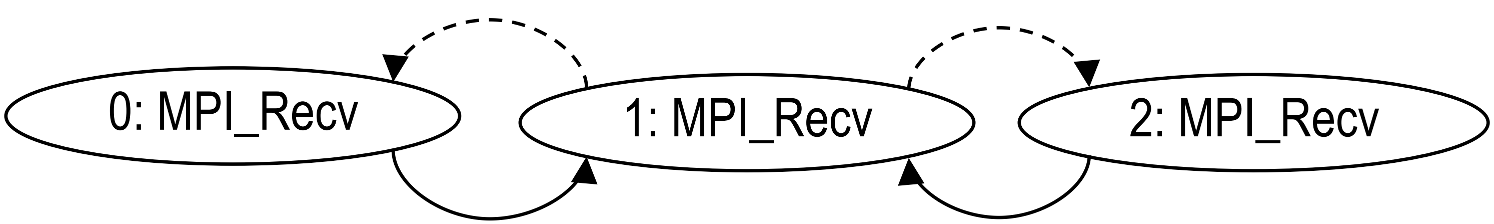
Task 0	Task 1	Task 2
MPI_Recv(from:1)	MPI_Recv(from:ANY);	MPI_Recv(from:1)

- What happens:
  - No call can progress, Deadlock
  - 0 waits for 1; 1 waits for either 0 or 1; 2 waits for 1

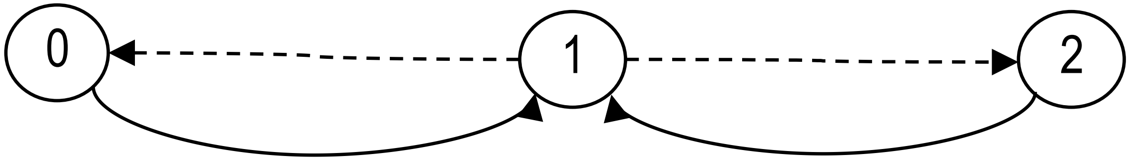
Error Classes – Deadlocks (7)

- How to visualize the "any/some" semantic?
  - There is the "Waits for all of" wait type => "AND" semantic
  - There is the "Waits for any of" wait type => "OR" semantic
  - Each type gets one type of arcs
    - AND: solid arcs
    - OR: Dashed arcs
- Visualization for Example 4:

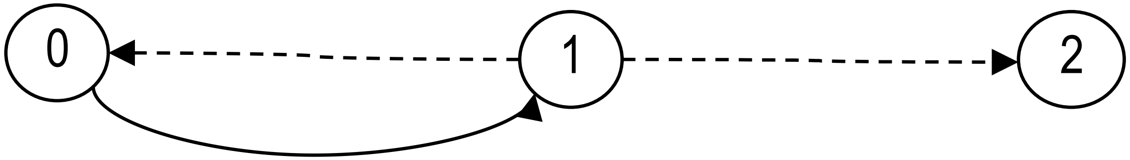
Task 0	Task 1	Task 2
MPI_Recv(from:1)	MPI_Recv(from:ANY);	MPI_Recv(from:1)



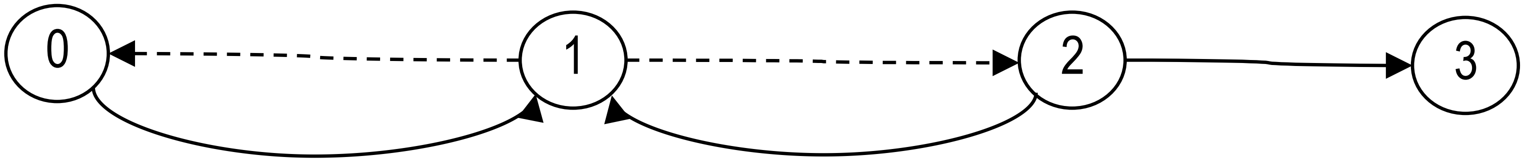
- Deadlock criterion for AND + OR
  - Cycles are necessary but not sufficient
  - A weakened form of a knot (OR-Knot) is the actual criterion
  - Tools can detect it and visualize the core of the deadlock
- Some examples:
  - An OR-Knot (which is also a knot, Deadlock):



  - Cycle but no OR-Knot (Not Deadlocked):



  - OR-Knot but not a knot (Deadlock):



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- **Avoiding Errors**
- Correctness Tools
- Runtime Error Detection
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Avoiding Errors

- The bugs you don't introduce are the best one:
  - Think, don't hack
  - Comment your code
  - Confirm consistency with asserts
  - Consider a verbose mode of your application
  - Use unit testing, or at least provide test cases
  - Set up nightly builds
    - MPI Testing Tool:
      - http://www.open-mpi.org/projects/mtt/
    - Ctest & Dashboards:
      - http://www.vtk.org/Wiki/CMake_Testing_With_CTest

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Correctness Tools

- Debuggers:
  - Helpful to pinpoint any error
  - Finding the root cause may be very hard
  - Won't detect sleeping errors
  - E.g.: gdb, TotalView, DDT
- Static Analysis:
  - Compilers and Source analyzers
  - Typically: type and expression errors
  - E.g.: MPI-Check
- Model checking:
  - Requires a model of your applications
  - State explosion possible
  - E.g.: MPI-Spin

- Runtime error detection:
  - Inspect MPI calls at runtime
  - Limited to the timely interleaving that is observed
  - Causes overhead during application run
  - E.g.: Intel Trace Analyzer, Umpire, **Marmot, MUST**
- Formal verification:
  - Extension of runtime error detection
  - Explores ALL possible timely interleavings
  - Can detect potential deadlocks or type missmatches that would otherwise not occur in the presence of a tool
  - For non-deterministic applications exponential exploration space
  - E.g.: ISP

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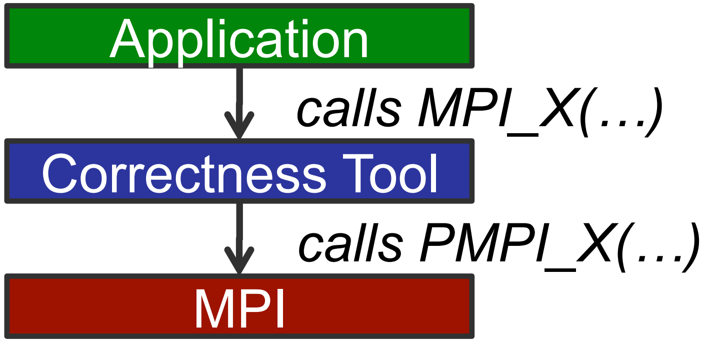
- A MPI wrapper library intercepts all MPI calls



- Checks analyse the intercepted calls
  - Local checks require data from just one task
    - E.g.: invalid arguments, resource usage errors
  - Non-local checks require data from multiple task
    - E.g.: type matching, collective verification, deadlock detection

Runtime Error Detection (2)

- Workflow:
  - Attach tool to target application (Link library to application)
  - Configure tool
    - Enable/disable correctness checks
    - Select output type
    - Enable potential integrations (e.g. with debugger)
  - Run application
    - Usually a regular mpirun
    - Non-local checks may require extra resources, e.g. extra tasks
  - Analyze correctness report
    - May even be available if the application crashs
  - Correct bugs and rerun for verification

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MUST – Overview

- MPI runtime error detection tool
- Successor of the Marmot and Umpire tools
  - Marmot provides many local checks
  - Umpire provides non-local checks
  - First goal: merge of functionality
  - Second goal: improved scalability
- OpenSource (BSD licenses)
- Currently in beta, first release Nov. 2011
- Partners:

Lawrence Livermore National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

ZIH Center for Information Services & High Performance Computing

http://tu-dresden.de/die_tu_dresden/zentrale_einrichtungen/zih/forschung/software_werkzeuge_zur_unterstuetzung_von_programmierung_und_optimierung/must

MUST – Features

- Local checks:
  - Integer validation
  - Integrity checks (pointers valid, etc.)
  - Operation, Request, Communicator, Datatype, Group usage
  - Resource leak detection
  - Memory overlap checks
- Non-local checks:
  - Collective verification
  - Lost message detection
  - Type matching (For P2P and collectives)
  - Deadlock detection (with root cause visualization)

MUST – Project State

- Local checks largely scalable
- Non-local checks:
  - Executed on a central process
  - This process is an MPI task taken from the application
  - Limited scalability ~100 tasks (Depending on application)
  - Can be disabled to provide scalability
- Future versions will provide distributed non-local checks
- Two types of outputs:
  - Logging to std::cout
  - Logging to an HTML file
- Uses a scalable tool infrastructure
  - Tool configuration happens at execution time

MUST – Usage

1) Compile and link application as usual
   - Link against the shared version of the MPI lib (Usually default)
2) Replace “mpiexec” with “mustrun”
   - E.g.: *mustrun –np 4 myApp.exe input.txt output.txt*
3) Inspect “MUST_Output.html” in run directory
   - “MUST_Deadlock.dot” exists in case of deadlock
   - Visualize with: *dot –Tps MUST_Deadlock.dot –o deadlock.ps*

- The mustrun script will use an extra process for non-local checks (Invisible to application)
- I.e.: “mustrun –np 4 …” will issue a “mpirun –np 5 …”
- Make sure to allocate the extra task in batch jobs

MUST – Example

- Example "vihps8_2011.c" :

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

MPI_Finalize ();
```

MUST – Example (2)

- Runs without any apparent issue with OpenMPI
- Are there any errors?

- Verify with MUST:
  - mpicc vihps8_2011.c –o vihps8_2011.exe
  - mustrun –np 4 vihps8_2011.exe
  - firefox MUST_Output.html

MUST – Example (3)

- First error: Type missmatch

MUST Outputfile

MUST Output, date: Thu Aug 25 09:04:01 2011.

Rank	Thread	Type	Message	From	References	MPI-Standard Reference
0		**Error**	A send and a receive operation use datatypes that do not match! Missmatch 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). 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) (Information on receive of count 8 with type:MPI_BYTE)	call MPI_Sendrecv	reference 1: call MPI_Sendrecv@rank 3 reference 2: call MPI_Sendrecv@rank 0 reference 3: call MPI_Type_contiguous@rank 3 reference 4: call MPI_Type_commit@rank 3	

MUST – Example (4)

- Second error: Send-send deadlock

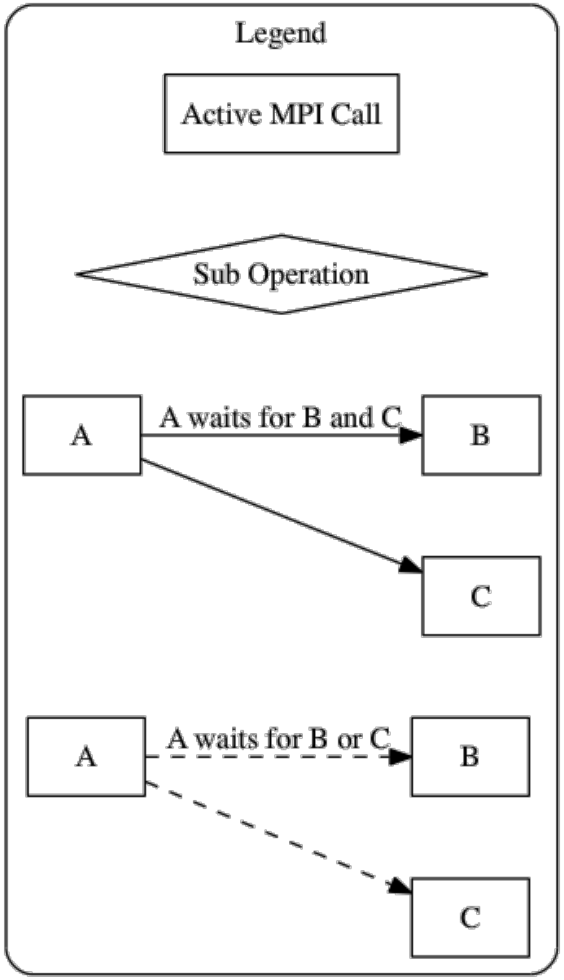
MUST Outputfile

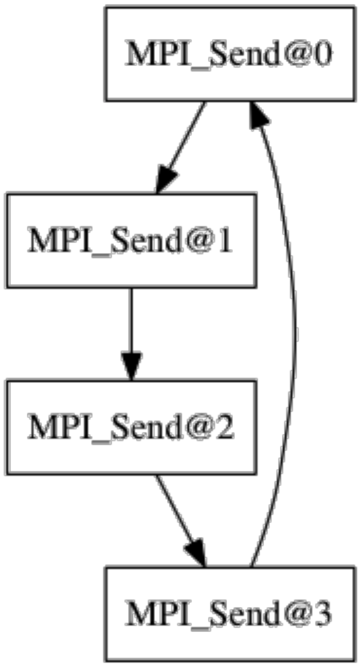
MUST Output, date: Thu Aug 25 09:04:01 2011.

Rank	Thread	Type	Message	From	References	MPI-Standard Reference
		Error	The application issued a set of MPI calls that can cause a deadlock! A graphical representation of this situation is available in the file named "MUST_Deadlock.dot". Use the dot tool of the graphviz package to visualize it, e.g. issue "dot -Tps MUST_Deadlock.dot -o deadlock.ps". The graph shows the nodes that form the root cause of the deadlock, any other active MPI calls have been removed. A legend is available in the dot format in the file named "MUST_DeadlockLegend.dot", further information on these graphs is available in the MUST manual. 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.		reference 1: call MPI_Send@rank 0 reference 2: call MPI_Send@rank 1 reference 3: call MPI_Send@rank 2 reference 4: call MPI_Send@rank 3	

MUST – Example (5)

- Visualization of deadlock (MUST_Deadlock.dot)





MUST – Example (6)

- Third error: Leaked datatype

MUST Outputfile

MUST Output, date: Thu Aug 25 09:04:01 2011.

Rank	Thread	Type	Message	From	References	MPI-Standard Reference
		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		reference 1: call MPI_Type_contiguous@rank 0 reference 2: call MPI_Type_commit@rank 0	

MUST – Operation Modes

- MUST causes overhead at runtime
- Default:
  - MUST expects a crash at any time
  - Blocking communication is used to ensure error detection
  - This can cause high overheads
- If your application doesn't crashs:
  - Add "**--must:nocrash**" to the mustrun command
  - MUST will use aggregated non-blocking communication in that case
  - Provides substantial speed up
- There are more options to mustrun, use "mustrun --help"

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- Hands On

Marmot – Overview

- Also an MPI runtime error detection tool
  - Focuses on local checks
  - Provides source locations and various integrations

- We will use Marmot as backup (If necessary)
- Usage:
  - Uses compiler wrappers: marmotcc myApp.c –o myApp.exe
  - Running with X tasks: mpirun –np X+1 myApp.exe
  - Output: “Marmot_<timestamp>.txt/html” in run directory

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Hands On – Build for MUST

- Disable any other tool (i.e. use mpif77/mpiifort)
- Build:

```
% make bt-mz NPROCS=4 CLASS=B
 ==========================================
  =      NAS PARALLEL BENCHMARKS 3.3       =
  =      MPI+OpenMP Multi-Zone Versions    =
  =      F77                               =
  ==========================================

cd BT-MZ; make CLASS=B NPROCS=4
make[1]: Entering directory
…
ifort -O2 -o ../bin/bt-mz.B.4 bt.o  initialize.o exact_solution.o …
make[1]: Leaving directory
```

VI-HPS

- Set up modules

```
module switch openmpi intelmpi
module load UNITE must
```

Aachen (Cluster-beta)

```
module load UNITE must
```

Juropa

- Go to bin directory

```
% cd bin
```

Hands On – Executing with MUST

- Create and edit the jobscript

```
cp ../jobscript/run.lsf ./
vim run.lsf
```

```
cp ../jobscript/run.msub ./
vim run.msub
```

- Jobscript:

MUST needs one extra process!

```
#!/usr/bin/env zsh
…
#BSUB -J mzmpibt
…
#BSUB -n 5
…
export OMP_NUM_THREADS=6

module swap openmpi intelmpi
module load UNITE must
module list

set -x

mustrun --must:mpiexec $MPIEXEC \
      --must:nocrash \
      -np 4 bt-mz_B.4
```

```
#!/bin/bas
…
#MSUB -l nodes=2:ppn=16
…
cd $PBS_O_WORKDIR

# benchmark configuration
export OMP_NUM_THREADS=4
PROCS=4
CLASS=B
EXE=./bt-mz_$CLASS.$PROCS

module load UNITE must

mustrun --must:nocrash \
      -np $PROCS --envall $EXE
```

Hands On – Executing with MUST

- Submit the jobscript:

```
bsub < run.lsf
```

```
msub run.msub
```

- Job output should read:

```
% cd bin
% mustrun --must:nocrash -np 4 bt-mz.A.4
 Weaver ... success
Code generation ... success
Build file generation ... success
Configuring intermediate build ... success
Building intermediate sources ... success
Installing intermediate modules ... success
Generating P^nMPI configuration ... success
Search for preloaded P^nMPI ... not found ... success
Executing application:
NAS Parallel Benchmarks (NPB3.2-MZ-MPI) - BT-MZ MPI+OpenMP Benchmark
…
Total number of threads:     16  (  4.0 threads/process)
Calculated speedup =     15.64

Time step     1
…
Verification Successful
```

BT – Marmot Results (1/2)

- Open the MUST output: <Browser> MUST_Output.html

MUST Outputfile

MUST Output, date: Thu Aug 25 12:19:02 2011.

Rank	Thread	Type	Message	From	References	MPI-Standard Reference
		Error	There are 1 communicators 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 communicators: -Communicator 1: Communicator created at reference 1 size=4		reference 1: call MPI_Comm_split@rank 1	
		Error	There are 1 communicators 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 communicators: -Communicator 1: Communicator created at reference 1 size=4		reference 1: call MPI_Comm_split@rank 2	
		Error	There are 1 communicators 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 communicators: -Communicator 1: Communicator created at reference 1 size=4		reference 1: call MPI_Comm_split@rank 3	
		Error	There are 1 communicators 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 communicators: -Communicator 1: Communicator created at reference 1 size=4		reference 1: call MPI_Comm_split@rank 0	

Conclusions

- Many types of MPI usage errors
  - Some errors may only manifest sometimes
  - Consequences of some errors may be “invisible”
  - Some errors can only manifest on some systems/MPIs
- Use MPI correctness tools
- Runtime error detection with MUST
  - Provides various correctness checks
  - Verifies type matching
  - Detects deadlocks
  - Verifies collectives
  - Currently limited scalability

Quick Sheet

- MUST is a runtime MPI error detection tool
- Usage:
  - Compile & link as always
  - Use "**mustrun**" instead of "mpirun"
  - Keep in mind to allocate 1 extra task in batch jobs
  - Add "**--must:nocrash**" if your application does not crashes
  - Open "**MUST_Output.html**" after the run completed/crashed