MPI-Checker – Static Analysis for MPI

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Motivation

Why is runtime analysis in HPC challenging?

- Large amount of resources are used
- State of the program can get very complex
  → Hard to survey
- Long run duration

Why is runtime analysis in HPC challenging?

- Large amount of resources are used
- State of the program can get very complex
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- Is there a way to complement dynamic tooling?

Static analysis

- Extensive static analysis of the source code
- Executed in the frontend
- Verify focused aspects of the code

In contrast to 'normal' compiler errors, warnings:

- More computational resources are used
- Better suited for domain specific checks

What are the benefits of static analysis for MPI?

- Analysis without running the program
- Unrelated to runtime resources
- Not affected by the commonness of a sequence at runtime
- Low maintenance effort

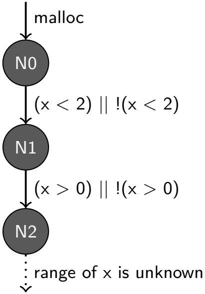
Clang Static Analyzer

Clang Static Analyzer

- Framework for static analysis: Core and checkers
- Provides two techniques to base a checker upon:
  - AST-based analysis
  - Path-sensitive analysis
- Descriptive HTML reports
- Extensible

AST-based analysis

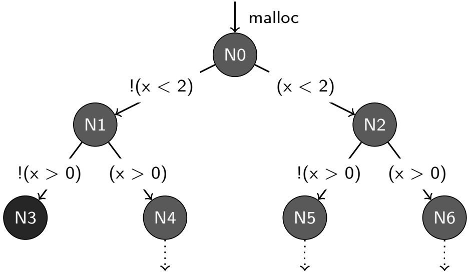
```
void memory(int x) {
    int *i = malloc(sizeof(int));
    if (x < 2) free(i);
    if (x > 0) free(i);
}
```



- Works if a check can verify an invariant locally
- No differentiation of distinct paths
- No assumptions can be made about the range of x

Path-sensitive analysis

```
void memory(int x) {
    int *i = malloc(sizeof(int));
    if (x < 2) free(i);
    if (x > 0) free(i);
}
```



- Distincts path sequences
- Symbolic execution
- Higher level of abstraction

Symbolic execution

- Symbolic representation of values, memory regions
- Variables are defined by constraints to ranges
- Each node represents a program point and state
- Operations are conceptually transitions between nodes

MPI-Checker

MPI-Checker

- Realised as a Clang Static Analyzer checker
- Hybrid: Provides AST-based and path-sensitive checks
- Can verify C and C++ code
- Checks are MPI implementation independent

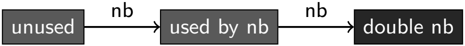
Path-sensitive Checks

Path-sensitive checks

- Check aspects of nonblocking communication
- Based on MPI request usage verification
- Request can be in different last user states
    - Unused, used by nonblocking call, used by wait
- Requests are tracked by their symbolic memory region

Double nonblocking

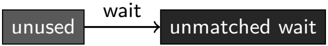
- Nonblocking call using a request that is already in use by a nonblocking call
- Checked when a call is symbolically executed



- Makes it impossible to wait for both nonblocking calls

Unmatched wait

- Checks for waits on requests not used by a nonblocking call



unused

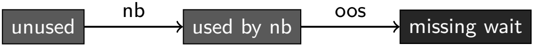
wait

unmatched wait

- Request is in an undefined state → undefined behavior

Missing wait

- Checks if a nonblocking call is not matched by a wait
- Checked when a symbol goes out of scope



- Nonblocking operation might not complete

AST-based Checks

Type mismatch

```
int buf;
MPI_Send(&buf, *, MPI_DOUBLE, *, *, *);
```

- Buffer type, MPI datatype tag correspondence

Type mismatch

```
int buf;
MPI_Send(&buf, *, MPI_DOUBLE, *, *, *);
```

- Buffer type, MPI datatype tag correspondence
- Clang already has type checking support limited to MPICH

→ MPI-Checker is MPI implementation independent

Type mismatch

```
int buf;
MPI_Send(&buf, *, MPI_DOUBLE, *, *, *);
```

- Buffer type, MPI datatype tag correspondence
- Support for all types defined by the MPI 3.1 standard
- Skipped: Custom buffer types, nullpointer constants, custom MPI types, MPI_BYTE, MPI_DATATYPE_NULL

Incorrect buffer referencing

```
int **buf;
MPI_Send(buf, *, MPI_INT, *, *, *);
```

- MPI functions specify void * as their buffer type
- Allows passing pointers not sufficiently dereferenced
- Subroutine of the type mismatch check

Invalid argument type

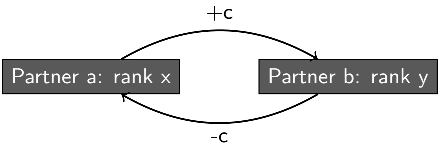
```
int x = 0;
MPI_Send(*, 1.1 + x, *, *, *, *);
```

- Check if non-integer types are used for rank, count or tag
- Can handle expressions of arbitrary complexity
- Corresponds to -Wfloat-conversion
  - -Wfloat-conversion can produce a lot of output
  - -Wfloat-conversion is neither included in -Wall nor -Wextra
- Convenience check

Unmatched point-to-point call

```
MPI_Send(*, 1, MPI_INT, f() + N + 3 + rank + 1, 0, C);
MPI_Recv(*, 1, MPI_INT, N + f() + 3 + rank - 1, 0, C, *);
```

- Checks for unmatched point-to-point operations
- Names, values must be equal
- Rank needs a specific notation
- Will be changed to a path-sensitive check



Unreachable call

```
if (rank == 0) {
    MPI_Send(*, 1, MPI_INT, rank + 1, 0, C);
    MPI_Recv(*, 1, MPI_INT, rank + 1, 0, C, *);
}
else if (rank == 1) {
    MPI_Send(*, 1, MPI_INT, rank - 1, 0, C);
    MPI_Recv(*, 1, MPI_INT, rank - 1, 0, C, *);
}
```

- Checks for deadlocks caused by blocking calls
- Based on the same point-to-point matching mechanism

Limitations

Limitations

- No assumption about runtime dependent results can be made
  → MPI_Waitany or MPI_Waitsome are not taken into account
- Heap allocated MPI_Request variables are not taken into account
- Analysis is limited to the scope of a translation unit

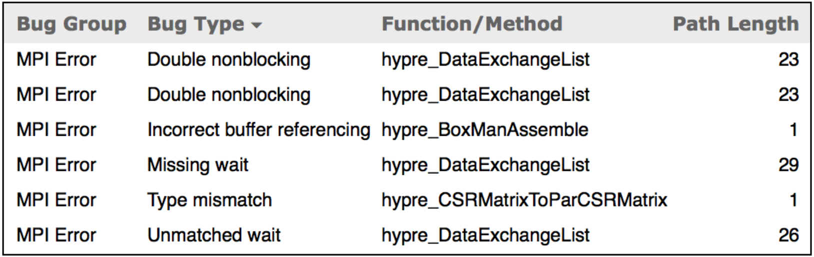
Evaluation

Evaluation

- AMG2013 ~75KLOC, 10x
- CombBLAS ~40KLOC, 2x
- OpenFFT ~5KLOC, 4x

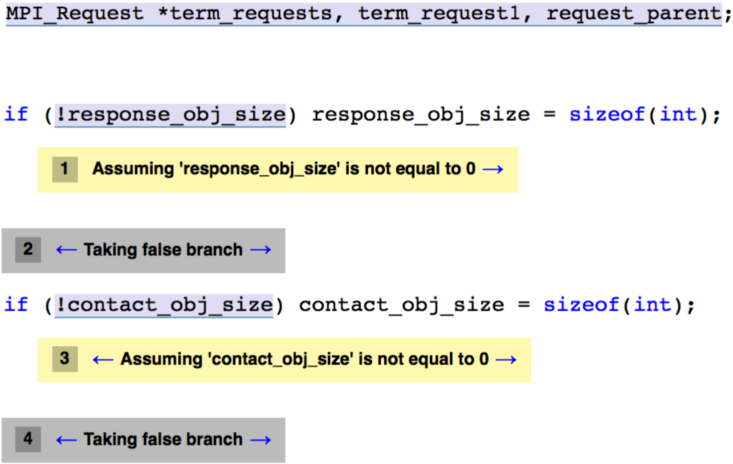
- No false positives but the likeliness of appearance differs
- Point-to-point checks were excluded

AMG2013 - Report overview



Bug Group	Bug Type ▾	Function/Method	Path Length
MPI Error	Double nonblocking	hypre_DataExchangeList	23
MPI Error	Double nonblocking	hypre_DataExchangeList	23
MPI Error	Incorrect buffer referencing	hypre_BoxManAssemble	1
MPI Error	Missing wait	hypre_DataExchangeList	29
MPI Error	Type mismatch	hypre_CSRMatrixToParCSRMatrix	1
MPI Error	Unmatched wait	hypre_DataExchangeList	26

AMG2013 - Detail report - Missing wait



```
MPI_Request *term_requests, term_request1, request_parent;

if (!response_obj_size) response_obj_size = sizeof(int);
```

1 Assuming 'response_obj_size' is not equal to 0 →

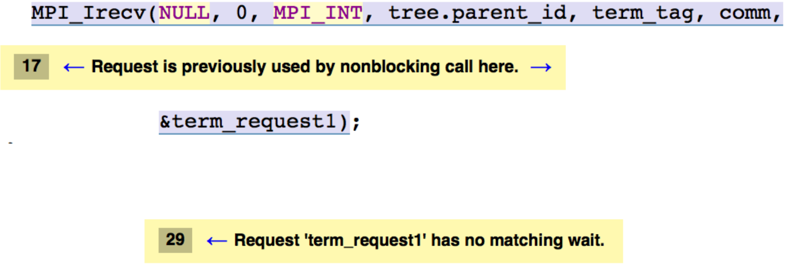
2 ← Taking false branch →

```
if (!contact_obj_size) contact_obj_size = sizeof(int);
```

3 ← Assuming 'contact_obj_size' is not equal to 0 →

4 ← Taking false branch →

AMG2013 - Detail report - Missing wait



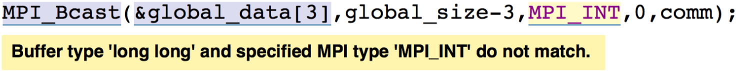
```
MPI_Irecv(NULL, 0, MPI_INT, tree.parent_id, term_tag, comm,
```

17 ← Request is previously used by nonblocking call here. →

```
                  &term_request1);
```

29 ← Request 'term_request1' has no matching wait.

AMG2013 - Detail report - Type mismatch



```
MPI_Bcast(&global_data[3],global_size-3,MPI_INT,0,comm);
```

Buffer type 'long long' and specified MPI type 'MPI_INT' do not match.

Future Work

Future work

- Merge MPI-Checker into Clang

- Detect race condition on buffer between nonblocking call and wait
- Path-sensitive point-to-point matching
- Possibility to type match custom types
- Analysis for a given process count
- ...

→ Adding new checks will now be a lot easier

Current State

Current state

- GitHub: https://github.com/0ax1/MPI-Checker

- Range of checks
- Limitations
- Examples
- Planned: Evaluation

Acknowledgments

Acknowledgments

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+ Clang mailing list

Questions?