A Modular LLVM-Based Contract Framework for Parallel Programming Models

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Parallel Programming

- Working with language-native parallel programming difficult
  - Different language $\rightarrow$ different API
  - Low-level, little abstraction
- In contrast: Parallel Programming Models
  - MPI [7]
  - OpenSHMEM [3]
  - GASPI [6]
  - ...
- (Sometimes) support for multiple languages
- Very error-prone...

How many issues can you spot in this tiny example?

At least 8 issues in this code example!

```
#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;
}
```

Our Approach

- Current example: MPI, but OpenSHMEM and other APIs are used as well
- Main languages: C/C++ and Fortran
- $\Longrightarrow$ Need tool for each language and programming model...

Our Approach

- Current example: MPI, but OpenSHMEM and other APIs are used as well
- Main languages: C/C++ and Fortran
- $\Longrightarrow$ Need tool for each language and programming model. . .
- Idea: “Move the model out of the tool, apply analysis independent of model”

Contract Basics

- Specify API assumptions in code
- Annotate additional information:
  - Preconditions / Premise: “What holds before this function?”
  - Postcondition: “What holds after it?”

[1] Feature delayed, but work continues [4]

Introduction

Contract Basics

- Specify API assumptions in code
- Annotate additional information:
  - Preconditions / Premise: “What holds before this function?”
  - Postcondition: “What holds after it?”
- Early C++20 draft[1]: `expects`, `ensures`, later `pre`, `post`
- Also available in other languages:
  - Prusti Project for Rust [1]
  - Kotlin Contracts [12]

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Applying Contracts

- Possible solutions using contracts (pseudocode):

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  - `<ret-type> MPI_* PRE{ call!(MPI_Init) }` $\Longrightarrow$ Ensures `MPI_Init` called
  - ```
    int MPI_Type_contiguous(..., MPI_Datatype* type) POST{
    no!  (call!(MPI_Irecv,*type))
    until!  (call!(MPI_Type_commit,type))}
    ```
    $\Longrightarrow$ Ensures type committed

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    ```

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Analyses unaware of model: No need for additional analyses for other models!

Inherently extensible: For other error classes / other models, simply add the annotations!
    ```

Architecture Considerations

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- For Proof of Concept:

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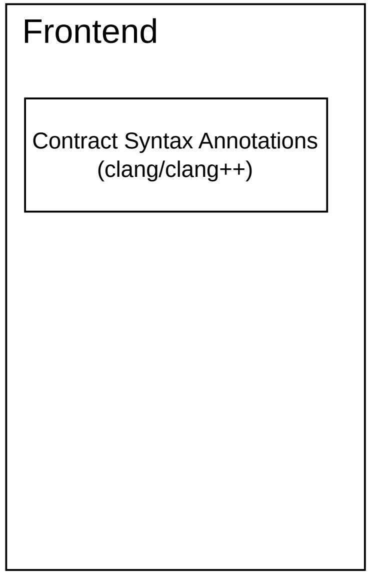

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  1. Develop contract syntax for considered languages $\Longrightarrow$ Function Annotations

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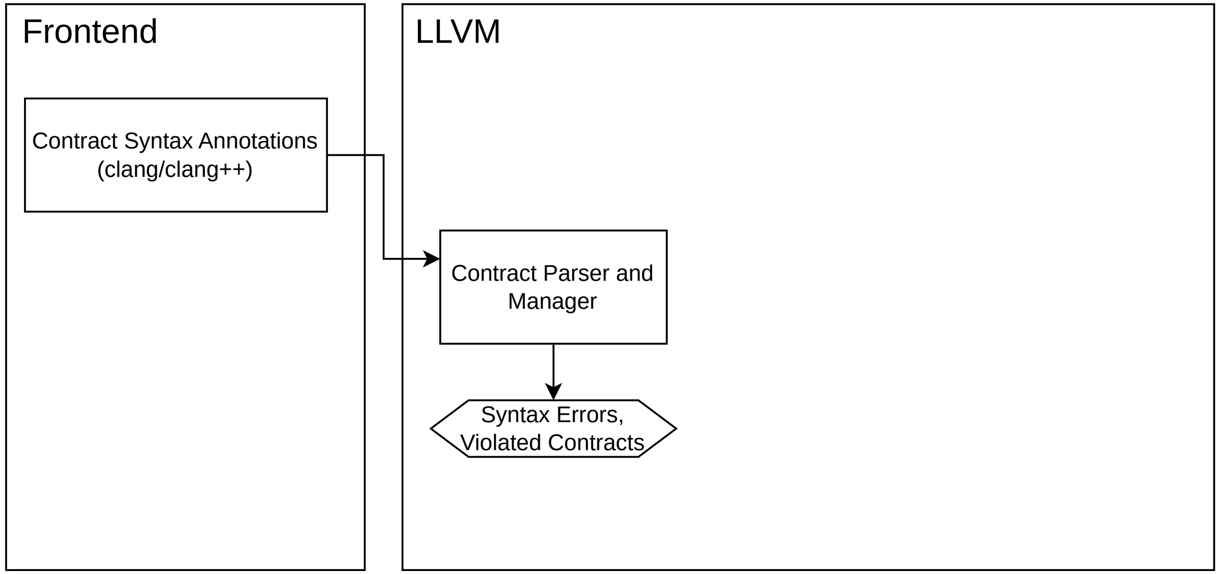

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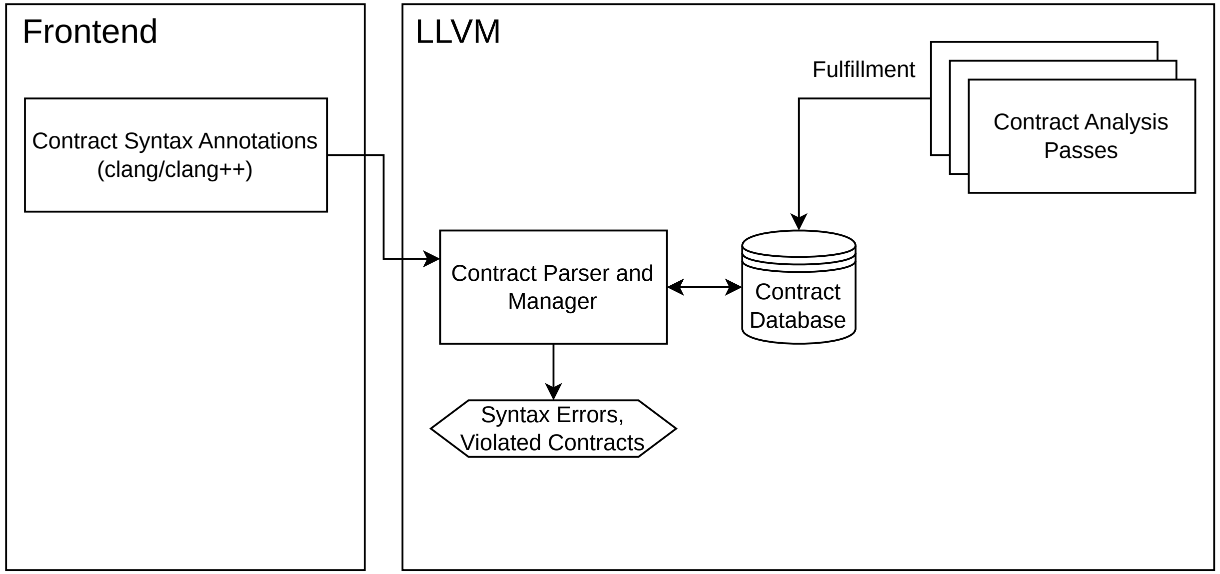

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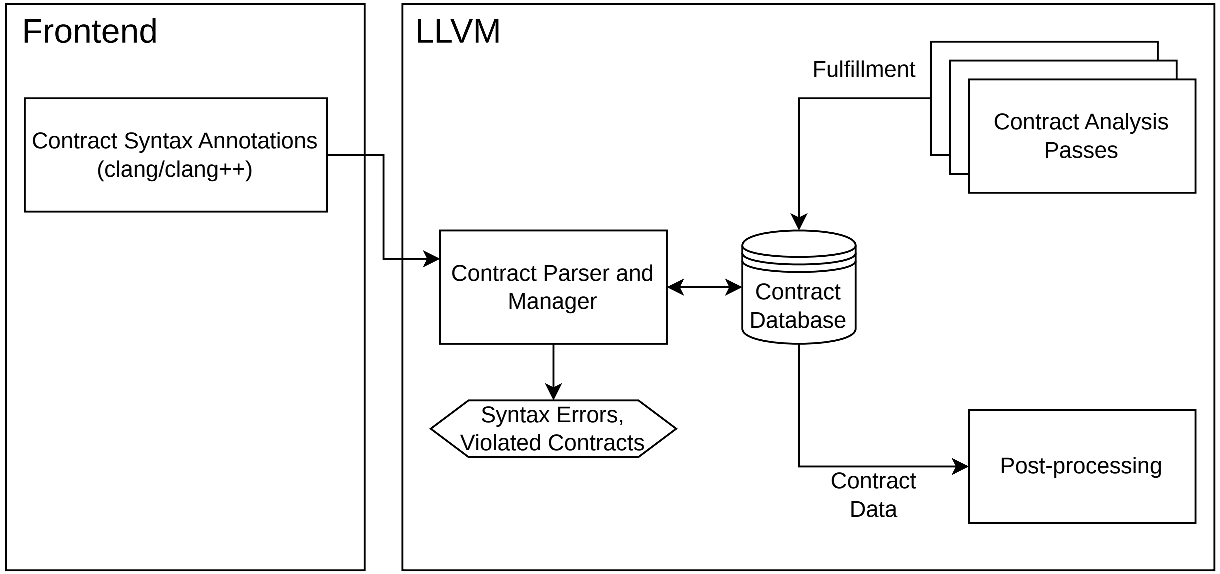

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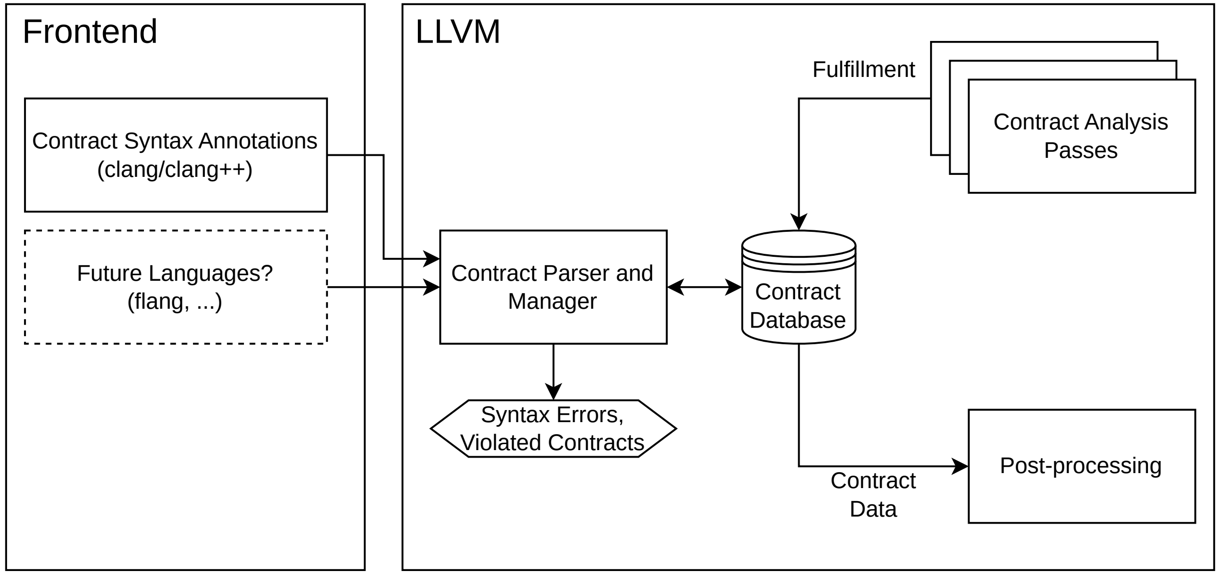

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Error Classes and Detection Methods

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  1. Request Lifecycle errors: Request not checked or request leaked
     - Request reuse before completion leaks memory

```
MPI_Request req;
MPI_Isend(&data, ..., &req);
MPI_Isend(&data, ..., &req);
// Only 2nd call is completed!
MPI_Wait(&req, MPI_STATUS_IGNORE);
```

Error Classes and Detection Methods

- Currently focusing on the following errors:
  1. Request Lifecycle errors: Request not checked or request leaked
  2. Resource (Datatype, Communicator) not initialized or freed
     - Many kinds of resources must be managed by the user manually
     - If not freed, data leaks occur. If not initialized, crashes or undefined behavior

```
MPI_Datatype type;
MPI_Type_contiguous(..., &type);
MPI_Send(&data, 1, type, ...);
```

Error Classes and Detection Methods

- Currently focusing on the following errors:
  1. Request Lifecycle errors: Request not checked or request leaked
  2. Resource (Datatype, Communicator) not initialized or freed
  3. Local Data Race
     - Buffers of nonblocking operations may not be written to, and sometimes also not read

```c
int value;
MPI_Win_fence(0, win);
if (rank == 0) {
    MPI_Get(&value, 1, ..., win);
    printf("Value is: %d", value);
}
MPI_Win_fence(0, win);
```


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  4. Missing Init/Finalize

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- Error classification leads to planned contract syntax
  - Require function called before/after current: `PRE / POST { call!(`*f*`) }`
  - Require a release operator: `POST { no! (`*op*`) until! (call!(`*f*`)) }`

Error Classes and Detection Methods

- Currently focusing on the following errors:
  1. **Request Lifecycle errors: Request not checked or request leaked**: `POST { call!(MPI_Wait) }`
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  4. **Missing Init/Finalize**: `PRE { call!(MPI_Init) }`
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  2. Resource (Datatype, Communicator) not initialized or freed
  3. **Local Data Race**: `POST { no! (read!(buf)) until! (call!(MPI_Win_fence)) }`
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- Error classification leads to planned contract syntax
  - Require function called before/after current: `PRE / POST { call!(`*f*`) }`
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Contract Abstraction

- Use ANTLR [14] to define formal grammar
- C/C++: Define contracts as function annotations
  - Helper macro: `#define CONTRACT(x) __attribute__((annotate("CONTRACT{" #x "}")))`

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Annotating using the helper macro:

```
int MPI_Finalize(void)
CONTRACT(PRE {call!(MPI_Init)});
```

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- Allow defining tags when functions fulfill similar purpose: `MPI_Win_fence` → `TAGS { rma_complete(1) }`

Annotating using the helper macro:

```
int MPI_Finalize(void)
CONTRACT(PRE {call_tag!(initialize)});
```

```
int MPI_Init(...) CONTRACT (TAGS { initialize })
int MPI_Init_thread(...) CONTRACT (TAGS { initialize })
```

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Annotating using the helper macro:

```
int MPI_Put(void* buf, ..., MPI_Win win) CONTRACT(
POST {
    no!
        write!(*0)
        // Do not write to buffer
    until!
        call_tag!(rma_complete,$:7)
        // Until communication was completed for the window
});
```

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- Allow defining tags when functions fulfill similar purpose: `MPI_Win_fence` → `TAGS { rma_complete(1) }`
- All contracts may be written at *any* function declaration:
  - Modify original model header (e.g. `mpi.h`)
  - Add additional declarations as separate header
  - Add declarations in source for specific analyses only
  - Chef's Choice: Separate header, include using `-include` preprocessor flag

Contract Abstraction

- Contract Manager: LLVM Analysis that reads `@llvm.global.annotations` $\rightarrow$ List of annotations
  - Calls parser, transform contract string into `ContractTree` representation
  - $\implies$ Analyses only interact with `ContractTree`, no contract language details needed

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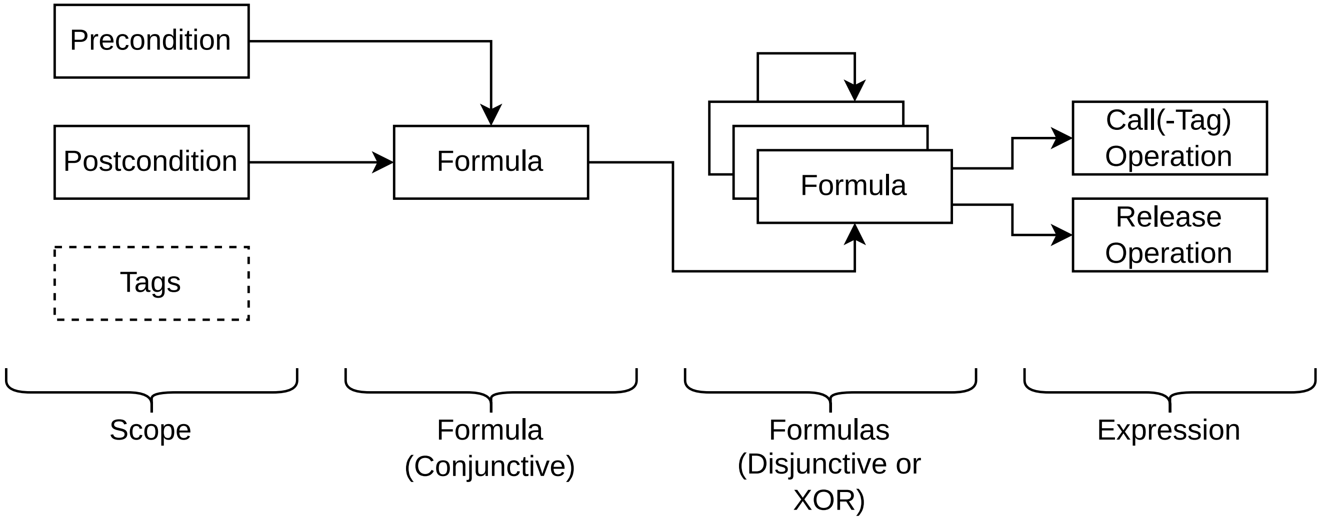

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- Example: “For an RMA operation, an epoch should exist (any kind, but not mixed)”

```
int MPI_Put(...) CONTRACT(
PRE {
    call_tag!(epoch_lock,$:7)} ^
    call_tag!(epoch_fence,$:7)^
    call_tag!(epoch_pscw,$:7)
});
```

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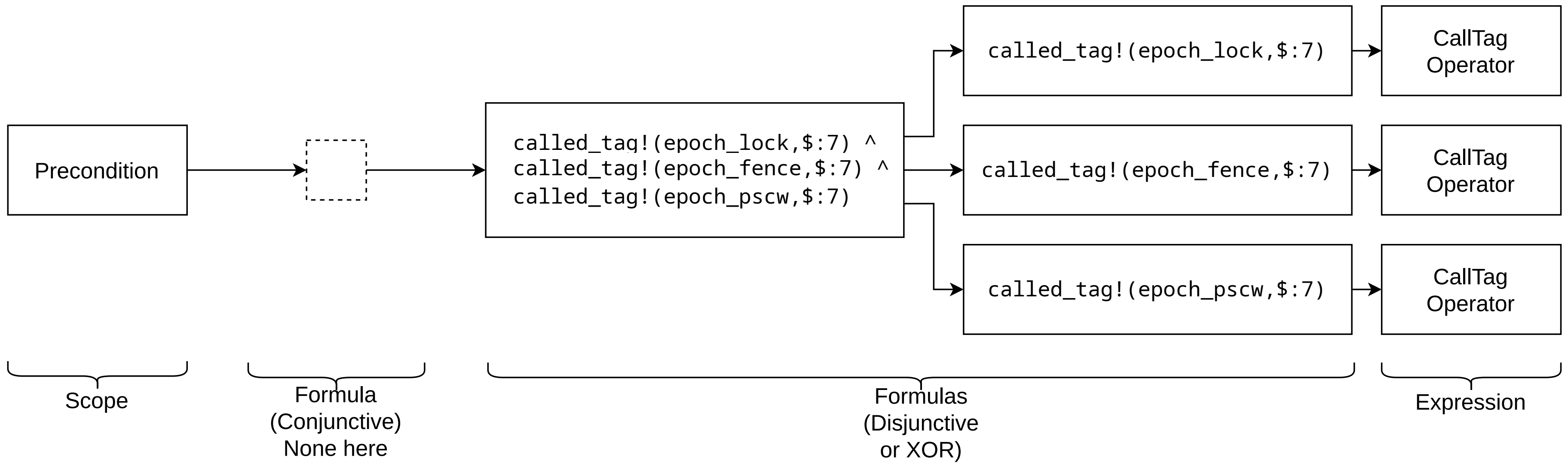

Error Classes and Detection Methods

Analysis

- Contract Verifiers: Implemented using Data Flow Analysis
  - `PreCall`: Check if function called previously
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  - `Release`: Check for conflict before release
- Verifiers share generic worklist algorithm with interprocedural support

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  - `PostCall`: Check if function called afterward
  - `Release`: Check for conflict before release
- Verifiers share generic worklist algorithm with interprocedural support. Current: $\{(1,2),(1,4)\}$

```
1 if (...)
2     MPI_Win_fence(win)
3     x++
4 print(x)
5 MPI_Put(&x, ..., win)
6 x = 1
7 return 0
```

Line	Result
1	**NOTCALLED**
2	CALLED
3	CALLED
4	CALLED
5	CALLED
6	CALLED
7	CALLED

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- Verifiers share generic worklist algorithm with interprocedural support. Current: $\{(2,3),(1,4)\}$

```
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3     x++
4 print(x)
5 MPI_Put(&x, ..., win)
6 x = 1
7 return 0
```

Line	Result
1	NOTCALLED
2	**PARAMCHECK**
3	CALLED
4	CALLED
5	CALLED
6	CALLED
7	CALLED

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  - `PreCall`: **Check if function called previously**: `MPI_Put` $\rightarrow$ `PRE { call!(MPI_Win_fence) }`
  - `PostCall`: Check if function called afterward
  - `Release`: Check for conflict before release
- Verifiers share generic worklist algorithm with interprocedural support. Current: $\{(4,5),(1,4)\}$

```
1 if (...)
2     MPI_Win_fence(win)
3     x++
4 print(x)
5 MPI_Put(&x, ..., win)
6 x = 1
7 return 0
```

Line	Result
1	NOTCALLED
2	PARAMCHECK
3	**PARAMCHECK**
4	**PARAMCHECK**
5	CALLED
6	CALLED
7	CALLED

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  - `PostCall`: Check if function called afterward
  - `Release`: Check for conflict before release
- Verifiers share generic worklist algorithm with interprocedural support. Current: $\{(4, 5)\}$

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5 MPI_Put(&x, ..., win)
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```

Line	Result
1	NOTCALLED
2	PARAMCHECK
3	PARAMCHECK
4	**NOTCALLED**
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7	CALLED

Error Classes and Detection Methods

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  - `PostCall`: Check if function called afterward
  - `Release`: Check for conflict before release
- Verifiers share generic worklist algorithm with interprocedural support. Current: $\emptyset$

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Line	Result
1	NOTCALLED
2	PARAMCHECK
3	PARAMCHECK
4	NOTCALLED
5	**ERROR**
6	**ERROR**
7	**ERROR**

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3	PARAMCHECK
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5	ERROR
6	ERROR
7	ERROR

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  - `Release`: **Check for conflict before release**: `MPI_Put` $\rightarrow$ `POST { no! (write!(*0)) until! ...}`
- Verifiers share generic worklist algorithm with interprocedural support . Current: $\{(5, 6)\}$

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```

Line	Result
1	FULFILLED
2	FULFILLED
3	FULFILLED
4	FULFILLED
5	**FORBIDDEN**
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7	FULFILLED

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7	**ERROR**

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- Verifiers share generic worklist algorithm with interprocedural support
- Post-processing pass outputs results for each contract
  - First: Resolve Formulas
  - Then: Print state, debug info of contract if violated or unknown

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```
## Contract violation detected! ##
--> Function: MPI_Put
--> Contract: CONTRACT{POST { no! (write!(*0)) ...}}
--> Postcondition Subformula Status: Violated
    --> Formula String: no!(write!(*0))...
    --> Error Info:
        [ContractVerifierRelease] Found store at main:6 which
          is in conflict with MPI_Put at main:5 before release
```


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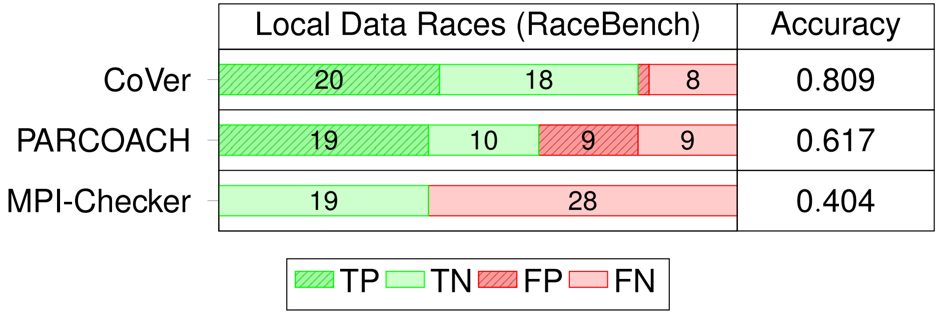
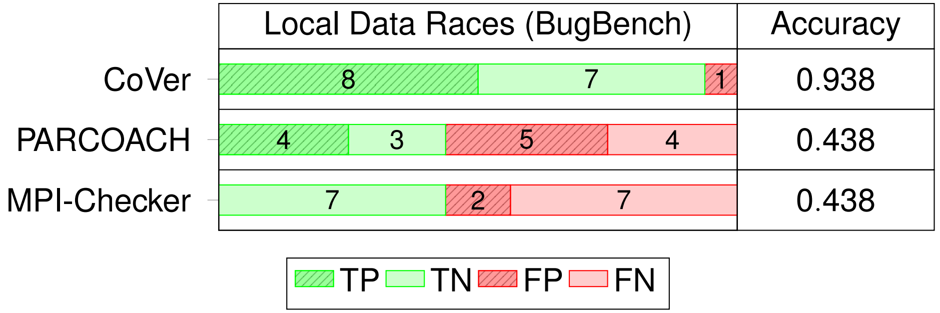
Experiment Setup

- Evaluate both accuracy and compilation overhead
- Accuracy:
  - Tests from MPI-BugBench (Level 1) [10]
  - Tests from RMARaceBench [16]
- Compilation Overhead:
  - LULESH [11]
  - miniVite [8]
  - PRK Stencil [17]
- Compare against PARCOACH-static [15] and MPI-Checker [5]

Evaluation

Accuracy





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- Significantly reduced FP rate

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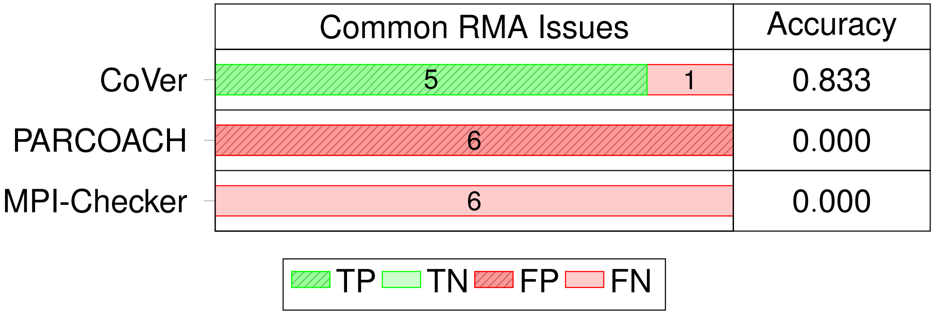

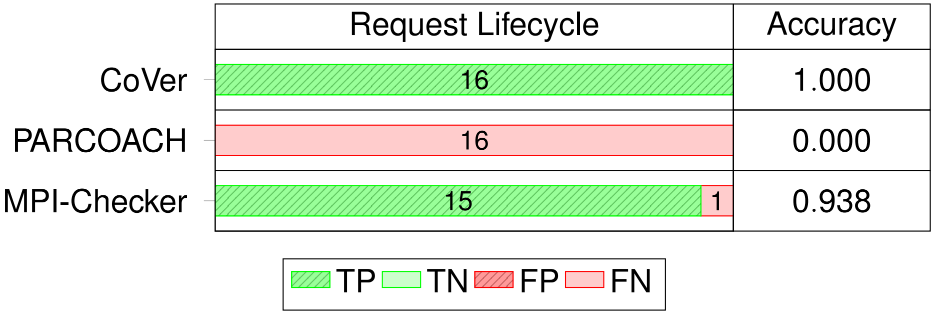

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- CoVer: Wide error class coverage
  - Adding checks often trivial
- CoVer and MPI-Checker detect similar request lifecycle issues

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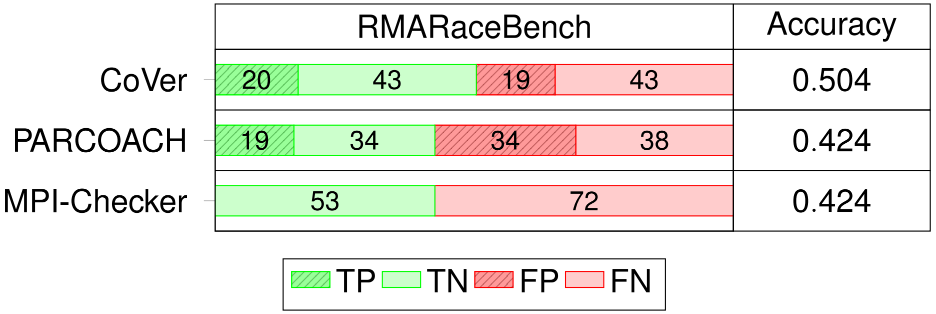

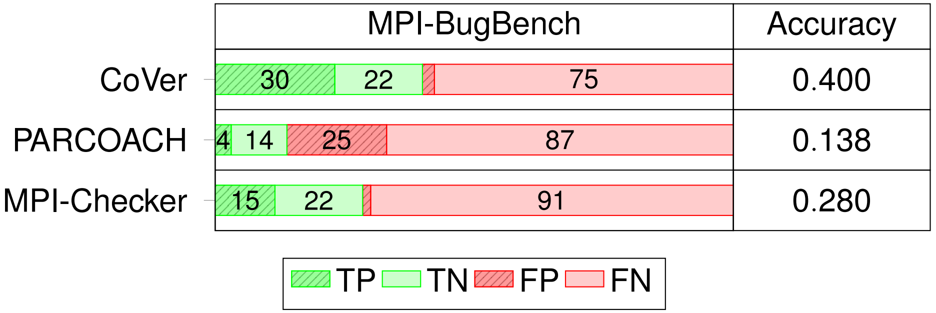

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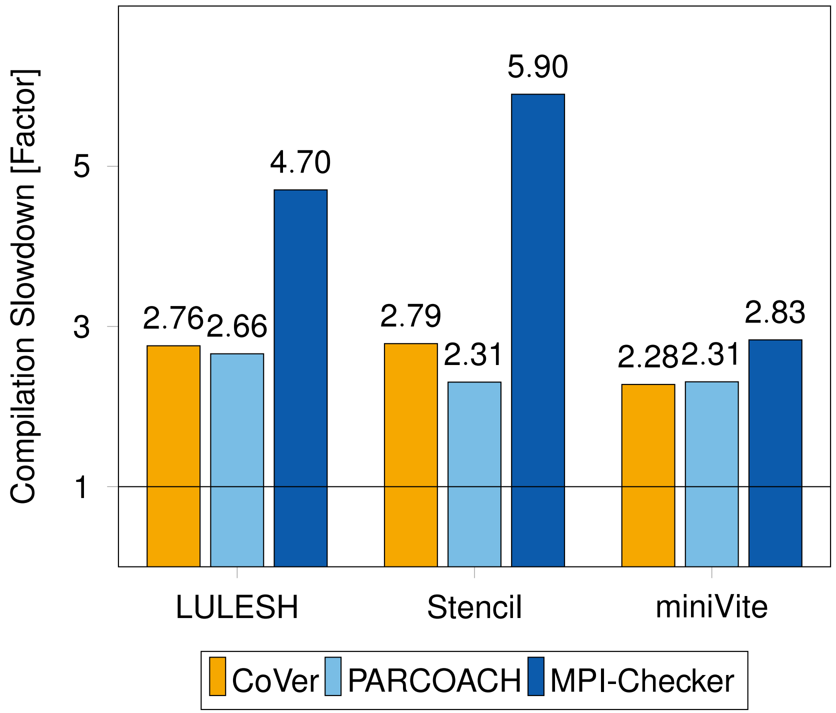
- Significantly reduced FP rate
- CoVer: Wide error class coverage
  - Adding checks often trivial
- CoVer and MPI-Checker detect similar request lifecycle issues
- Overall: High Accuracy using wide coverage
- But: (In total) Higher FP rate than MPI-Checker
  - Caused by ignoring branch condition

Evaluation

Overhead



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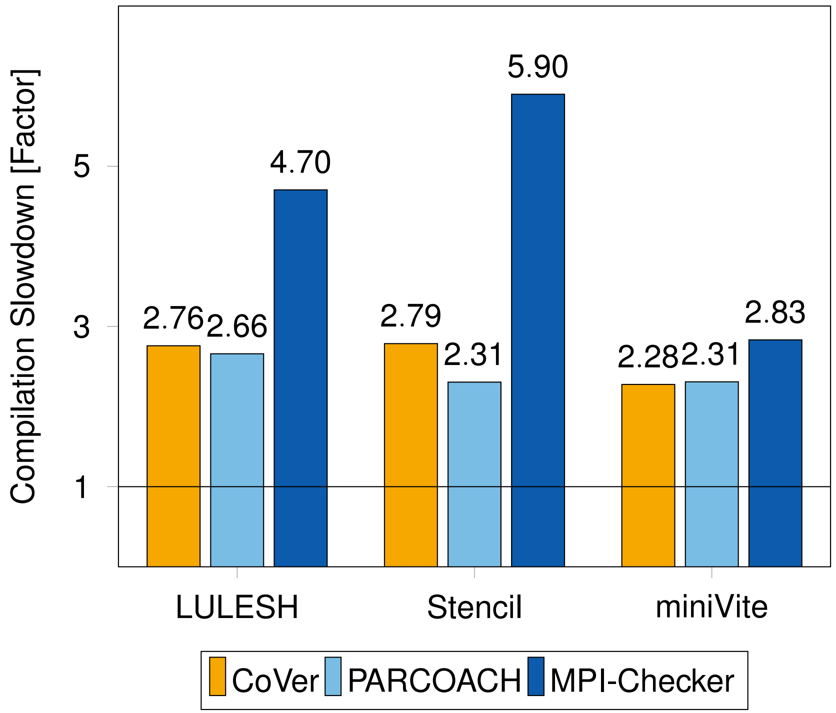

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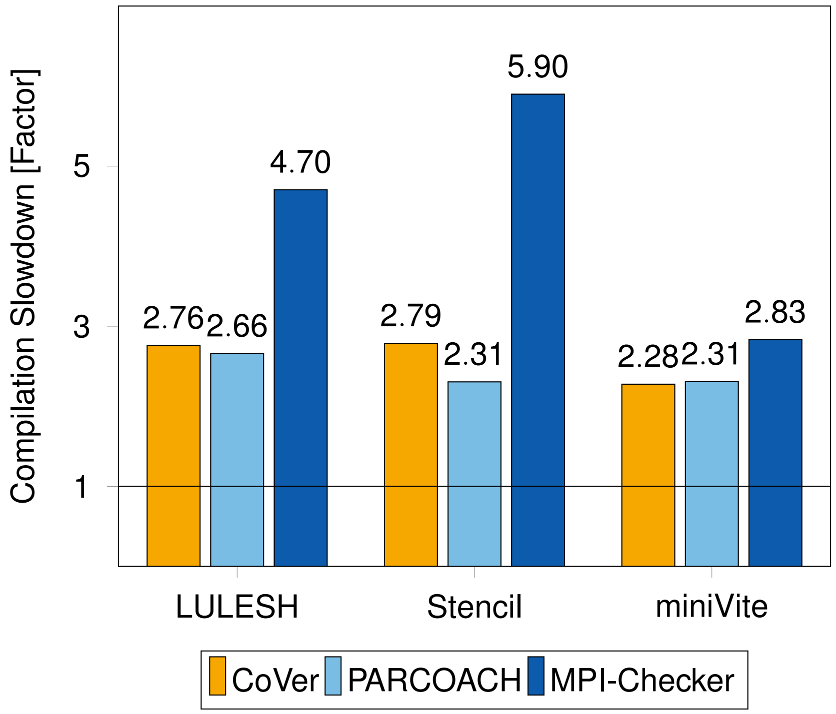

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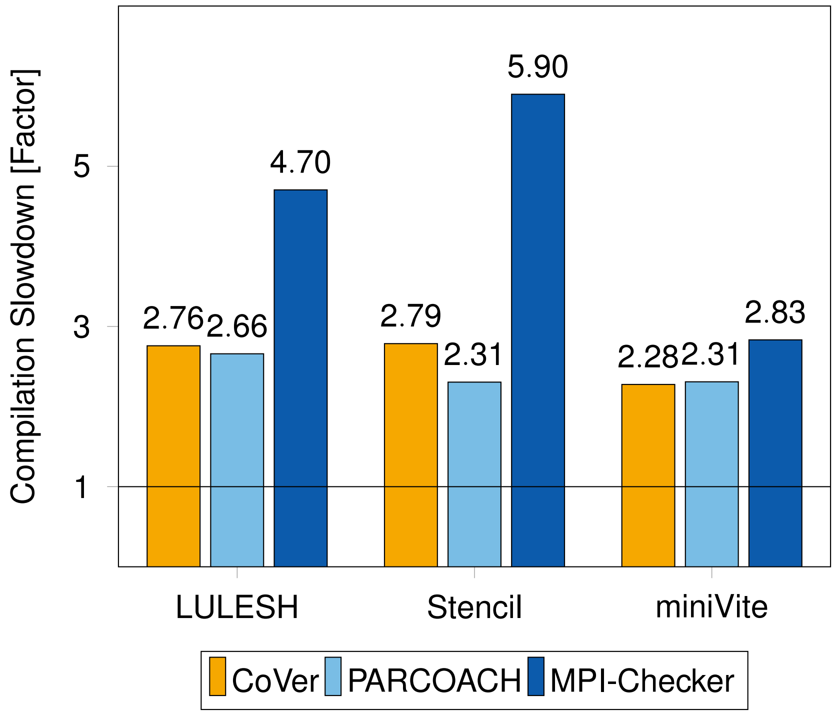

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  - Disadvantage shown in the graph...

Related Work

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- SPMD IR [2] is an approach unifying multiple programming models
  - Generic, but non-modular: Cannot extend without source modification
  - Both error classes and supported models static once tool shipped

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How many issues can you spot in this tiny example?

At least 8 issues in this code example!

```
#include <mpi.h>
#include <stdio.h>
int main (int argc, char** argv)
{
   int rank, size, buf[8];

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

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MPI + GPU Correctness Checking with MUST
46th VI-HPS Workshop
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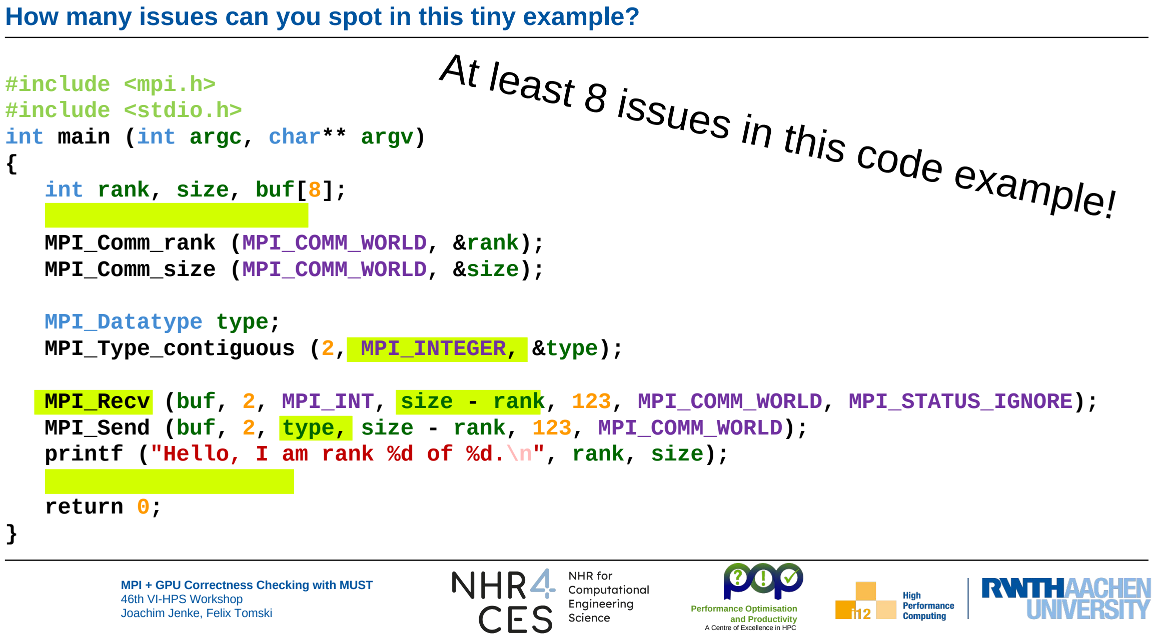

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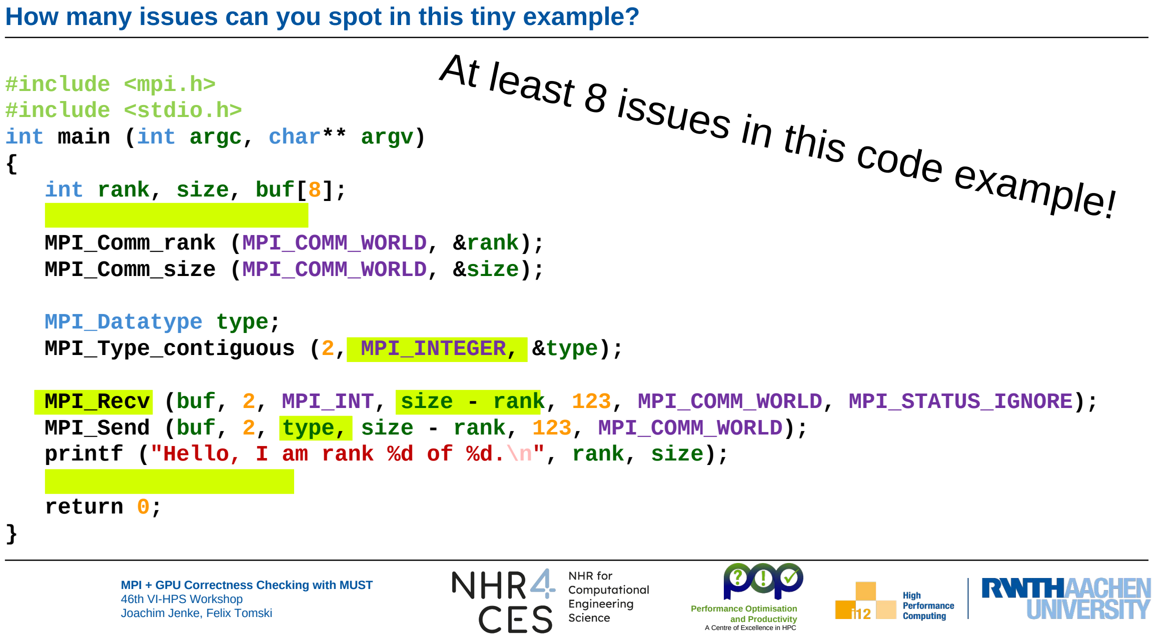
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Thank you for your attention!

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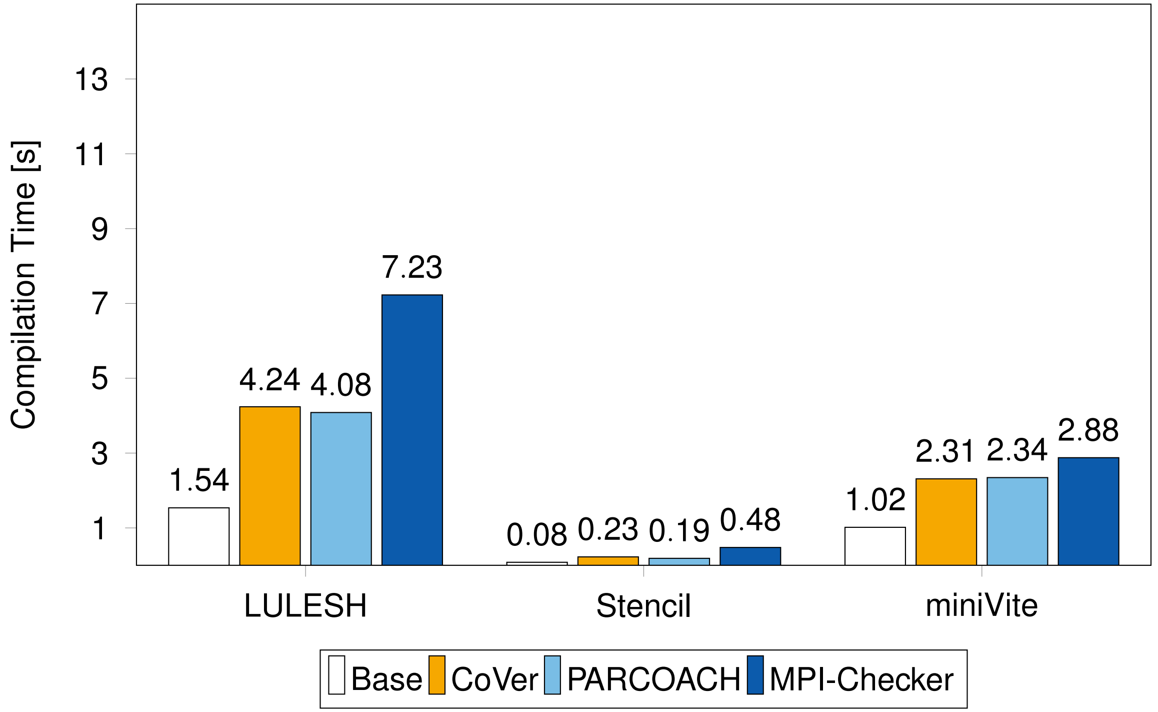
Common False-Positive Causes

```
if (rank == 0) {
    MPI_Irecv(buf, ..., MPI_REQUEST_NULL);
}
if (rank == 1) {
    MPI_Isend(buf, ..., &mpi_request_0);
}
MPI_Wait(&mpi_request_0, MPI_STATUS_IGNORE);
```

- Branch conditions not checked
  - Future Work: Evaluate Multi-Value analysis for improvement
- Path with both conditions evaluated to true checked
- $\implies$ Invalid data race report
- Duplicate error: Unmatched Wait, Missing Wait

Absolute Compilation Time Comparison



Output from introduction example

```
## Contract violation detected! ##
--> Function: MPI_Comm_rank
--> Contract: ...
    --> Message: "Missing Initialization call"
...
    --> Message: "Missing Finalization call"
// Init-/Finalization errors left out for other functions

## Contract violation detected! ##
--> Function: MPI_Type_contiguous
--> Contract: ...
    --> Message: "Type not committed before use"
```