SPMD IR: Unifying SPMD and Multi-value IR Showcased for Static Verification of Collectives

Semih Burak, I. Ivanov, J. Domke, M. Müller

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Motivation

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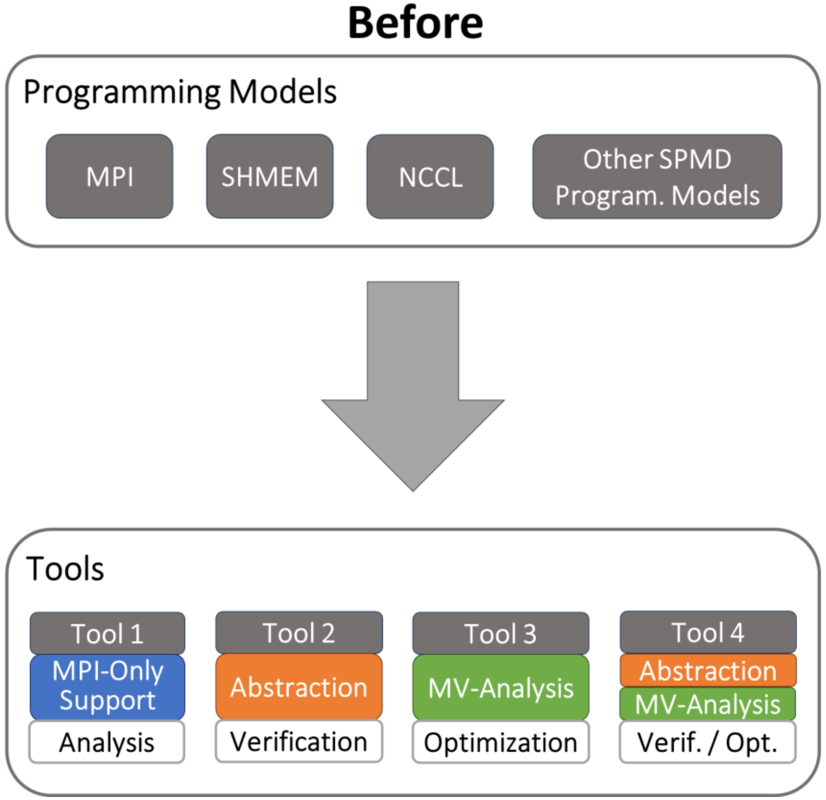

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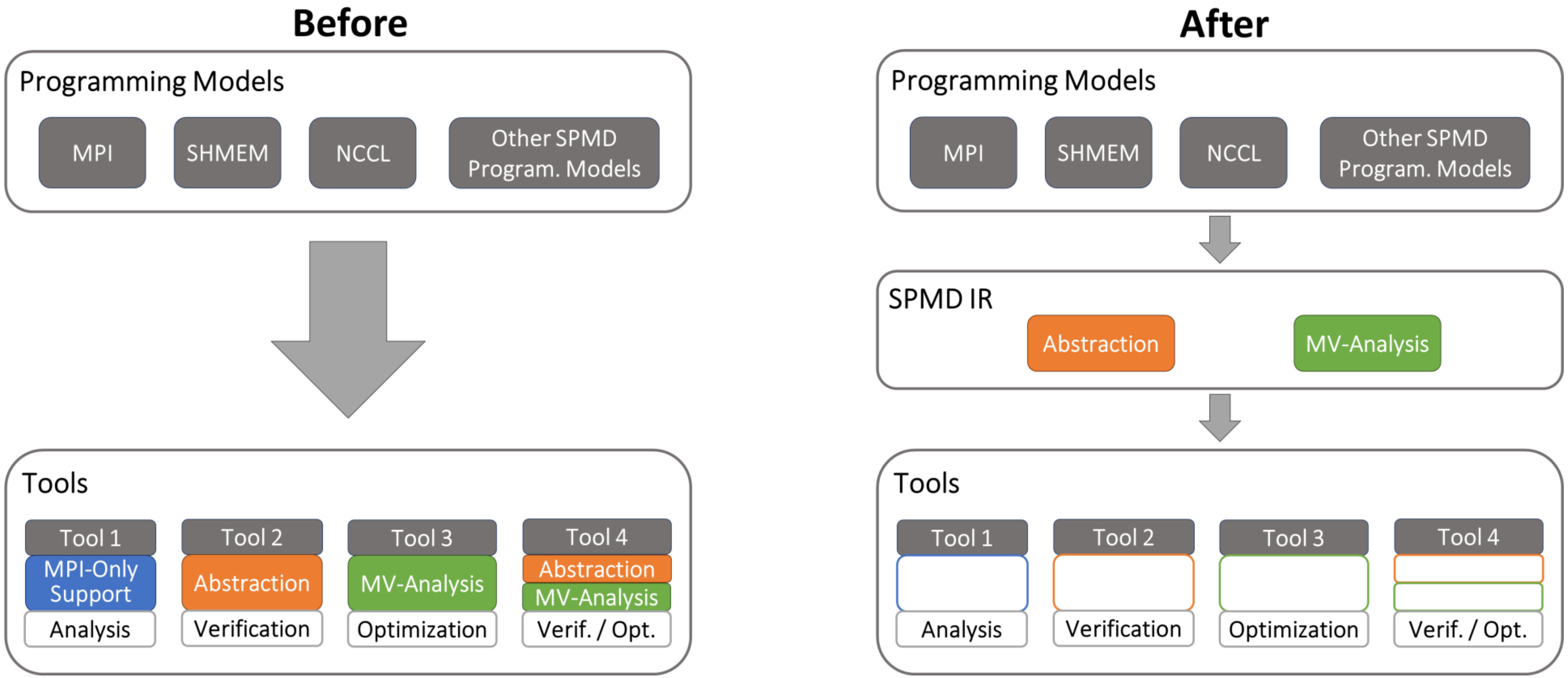

Before

Programming Models

MPI

SHMEM

NCCL

Other SPMD Program. Models

Tools

Tool 1

MPI-Only Support

Analysis

Tool 2

Abstraction

Verification

Tool 3

MV-Analysis

Optimization

Tool 4

Abstraction

MV-Analysis

Verif. / Opt.

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SPMD IR

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Outline

- Background
  - MLIR
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  - Extended Multi-Value Analysis
  - Scope
  - Example
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- Discussion

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  - is more extensible, reusable
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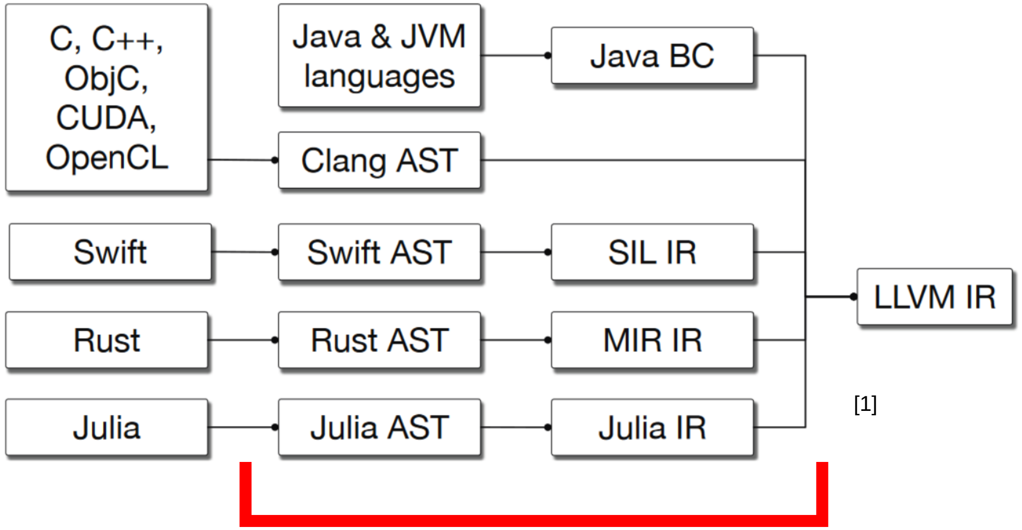

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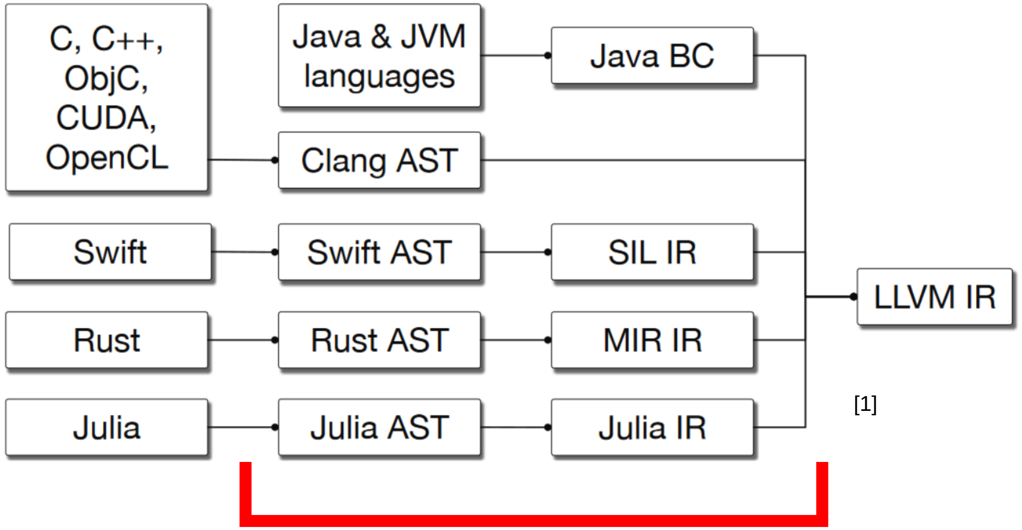

- Idea:
  - Express SPMD-related information in its own dialect and a set of attributes
  - Next to other special-purpose dialects, e.g., for shared-memory parallelism

MLIR also helps here, replacing custom high-level IRs

Background: MLIR (2)

```
func.func @main(...) -> i32  {
  ... // define constants and other omitted operations
  %ref = memref.alloca(%size) : (index) -> memref<?xf64>
  ... // fill "array" (ref) with values
  func.call @multPosByX(%ref, %size, %c_x):(memref<?xf64>, index, f64) -> ()
  ...
}
```

- Red highlights the dialects
- Orange the values
- Blue the types

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func.func @multPosByX(%arg_ref: memref<?xf64>, %arg_size: index,
                              %arg_c_x: f64) -> () {
  %c0_index = arith.constant() {value = 0 : index} () -> index
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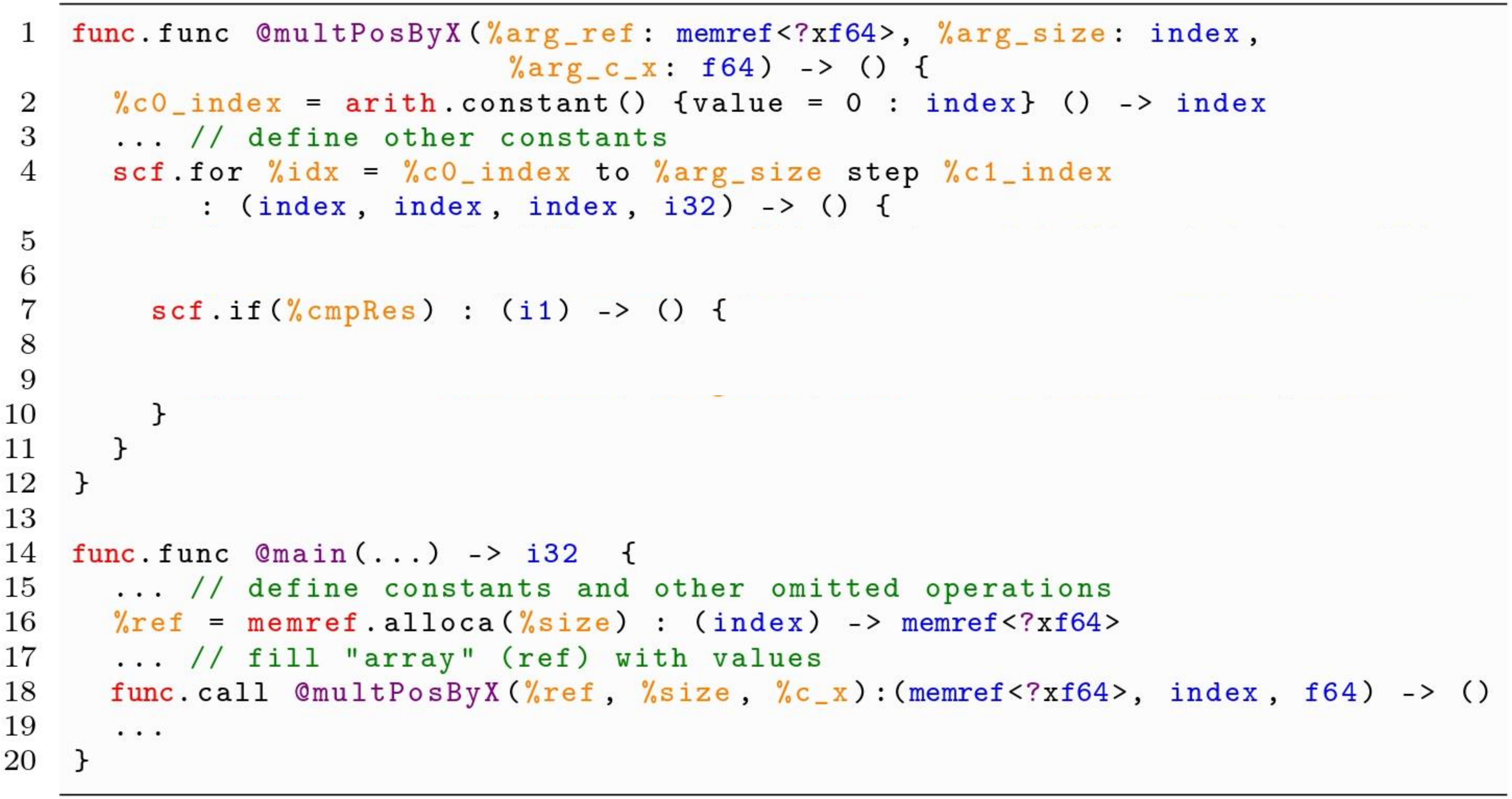

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  %c0_index = arith.constant() {value = 0 : index} () -> index
  ... // define other constants
  scf.for %idx = %c0_index to %arg_size step %c1_index
       : (index, index, index, i32) -> () {


    scf.if(%cmpRes) : (i1) -> () {


    }
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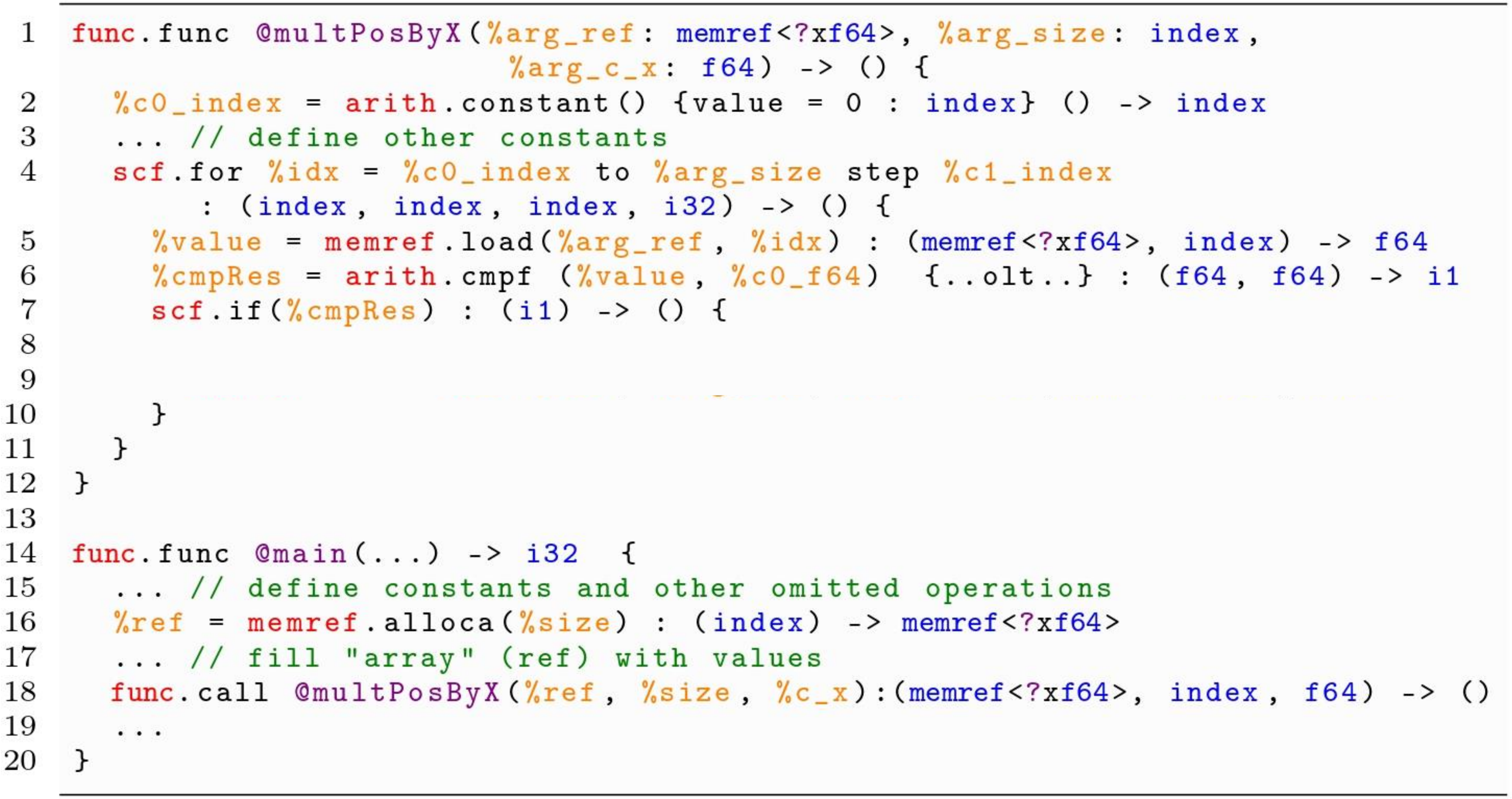

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  ... // define other constants
  scf.for %idx = %c0_index to %arg_size step %c1_index
        : (index, index, index, i32) -> () {
    %value = memref.load(%arg_ref, %idx) : (memref<?xf64>, index) -> f64
    %cmpRes = arith.cmpf (%value, %c0_f64)  {..olt..} : (f64, f64) -> i1
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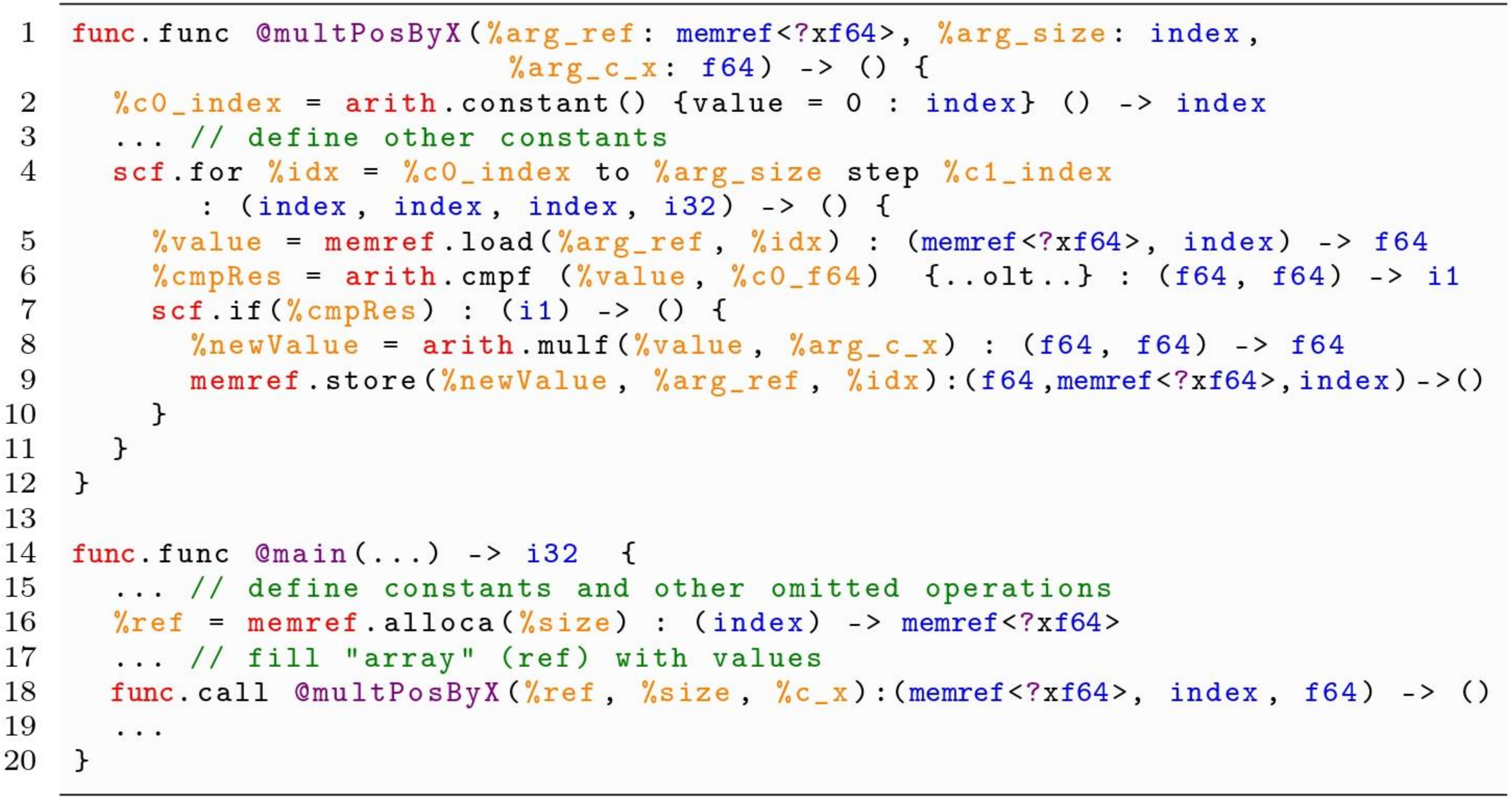

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    scf.if(%cmpRes) : (i1) -> () {
      %newValue = arith.mulf(%value, %arg_c_x) : (f64, f64) -> f64
      memref.store(%newValue, %arg_ref, %idx):(f64,memref<?xf64>,index)->()
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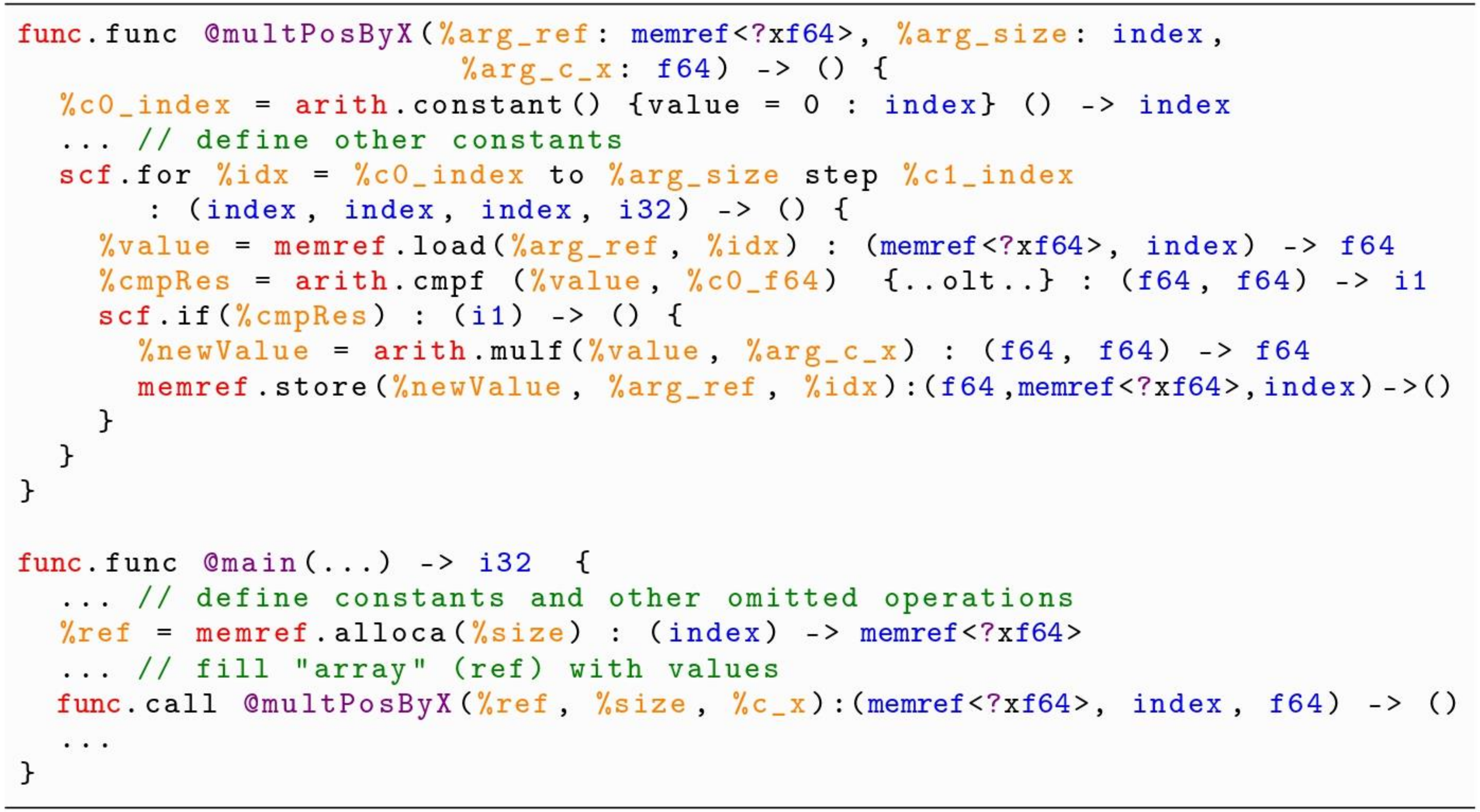

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- As each dialect can seamlessly interact with other dialects
  - MLIR provides a toolset to develop an expressive IR composed of multiple levels and semantics

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- A variable or value is called multi-value (MV)
  - if its runtime-value may differ for a subset of processes
  - and called single-value (SV) otherwise

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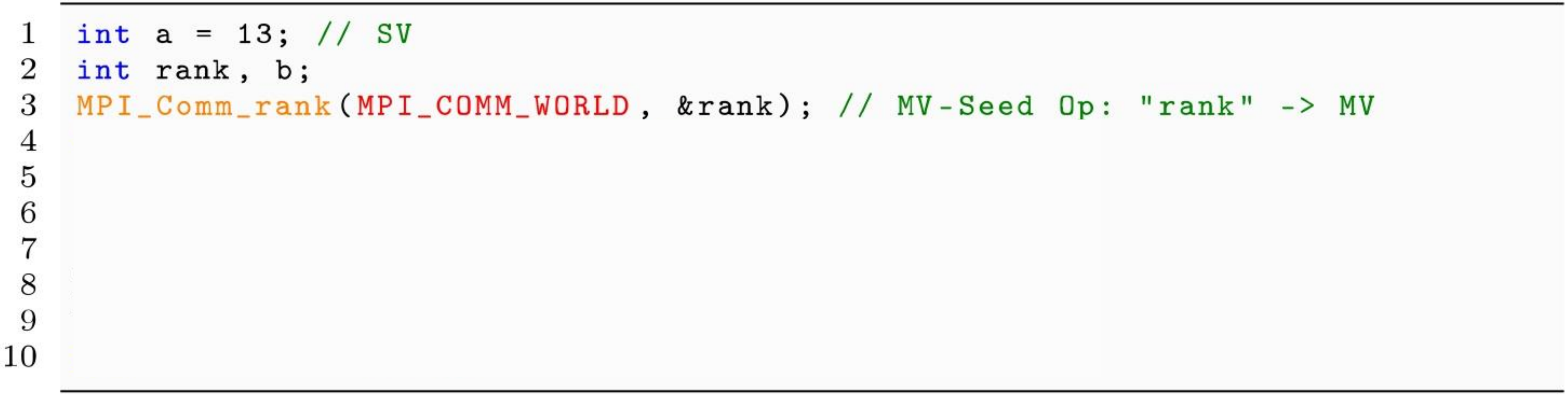

```
int a = 13; // SV
int rank, b;
MPI_Comm_rank(MPI_COMM_WORLD, &rank); // MV-Seed Op: "rank" -> MV
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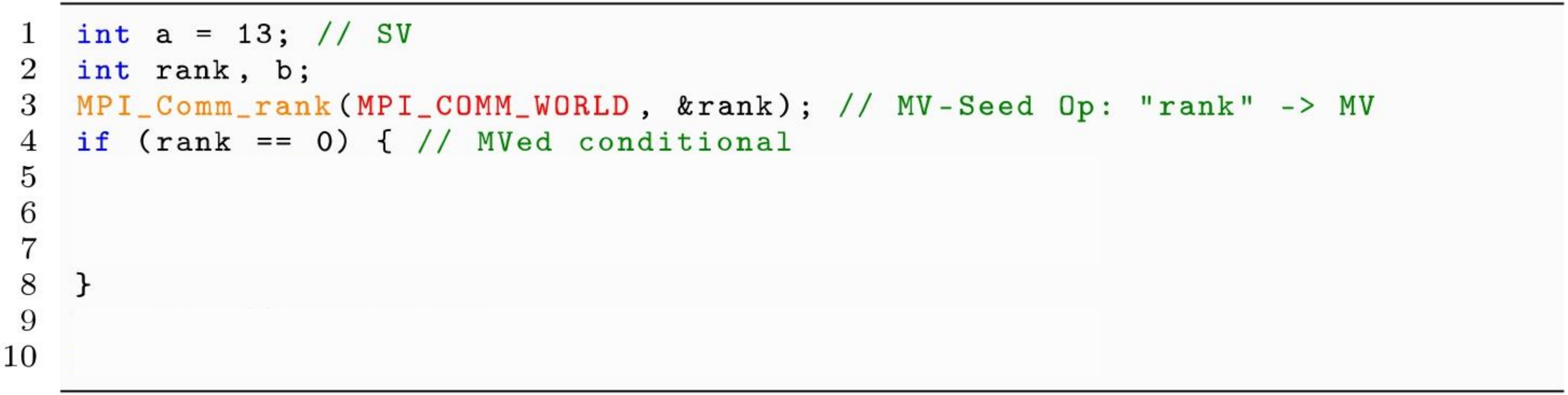

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int a = 13; // SV
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if (rank == 0) { // MVed conditional



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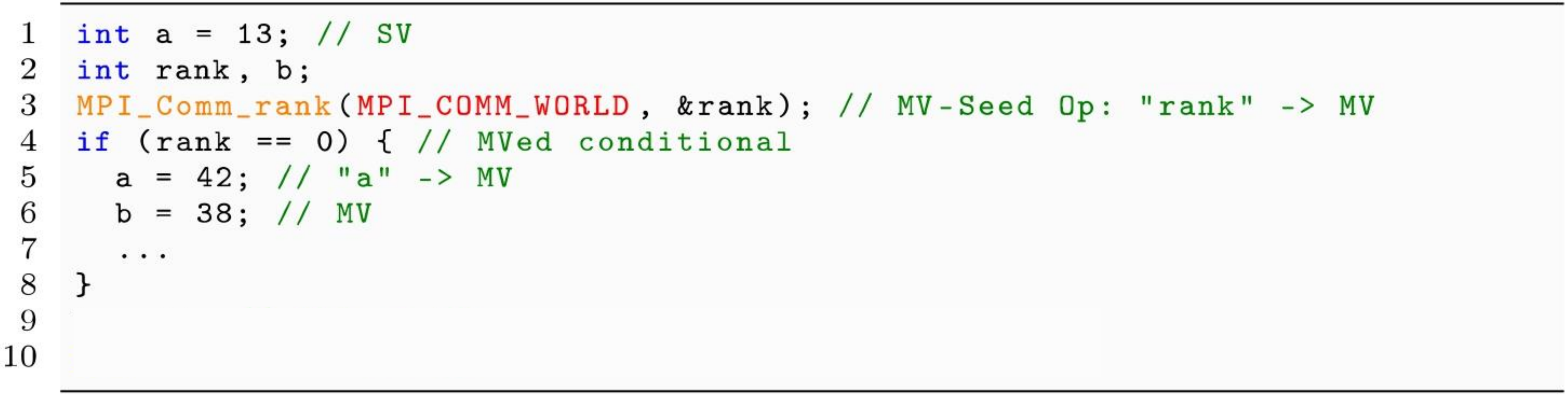

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int rank, b;
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if (rank == 0) { // MVed conditional
  a = 42; // "a" -> MV
  b = 38; // MV
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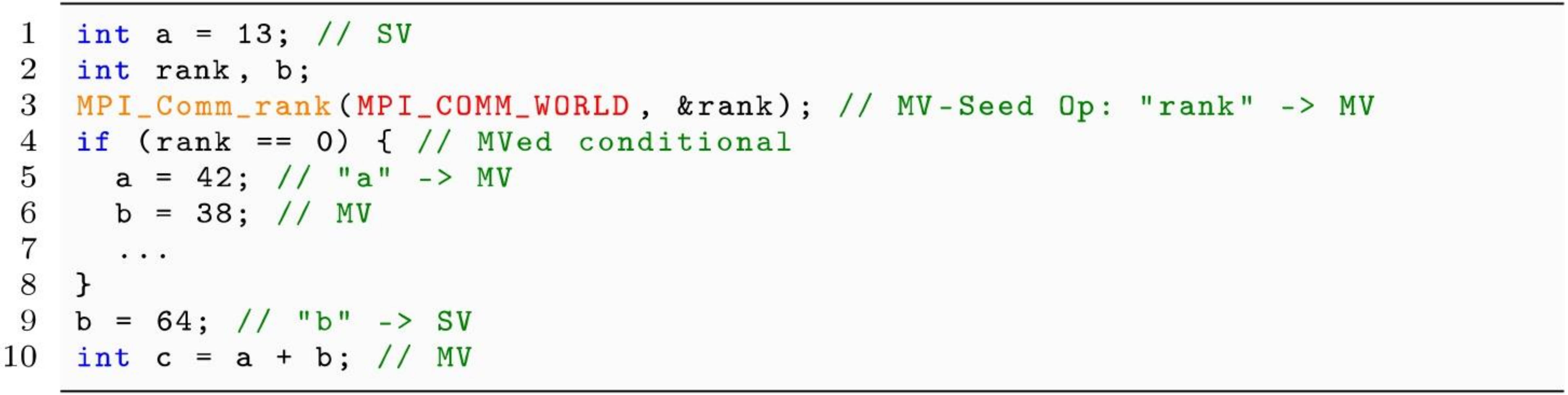

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}
b = 64; // "b" -> SV
int c = a + b; // MV
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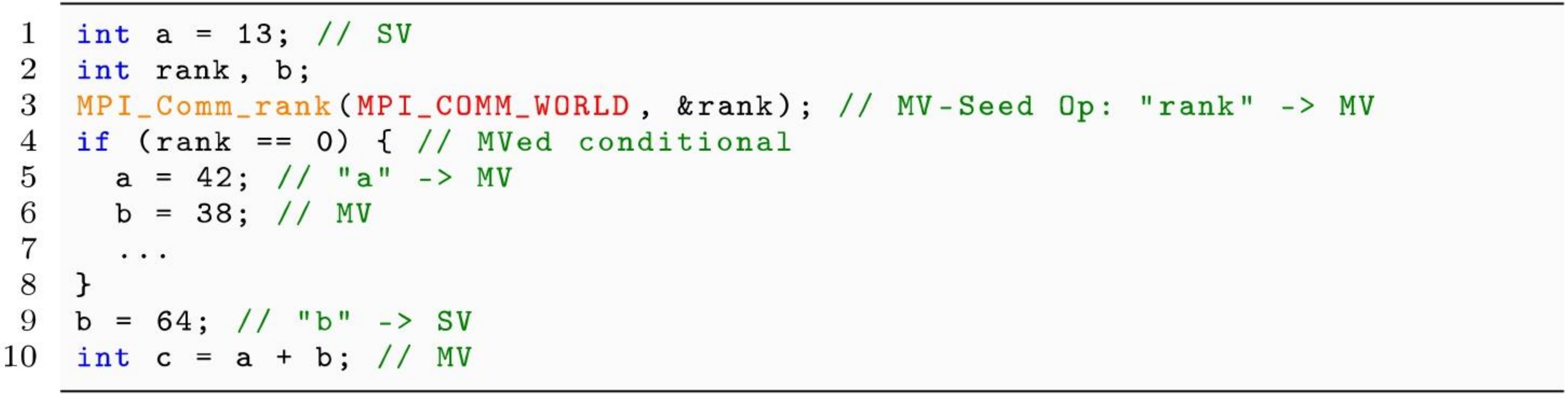

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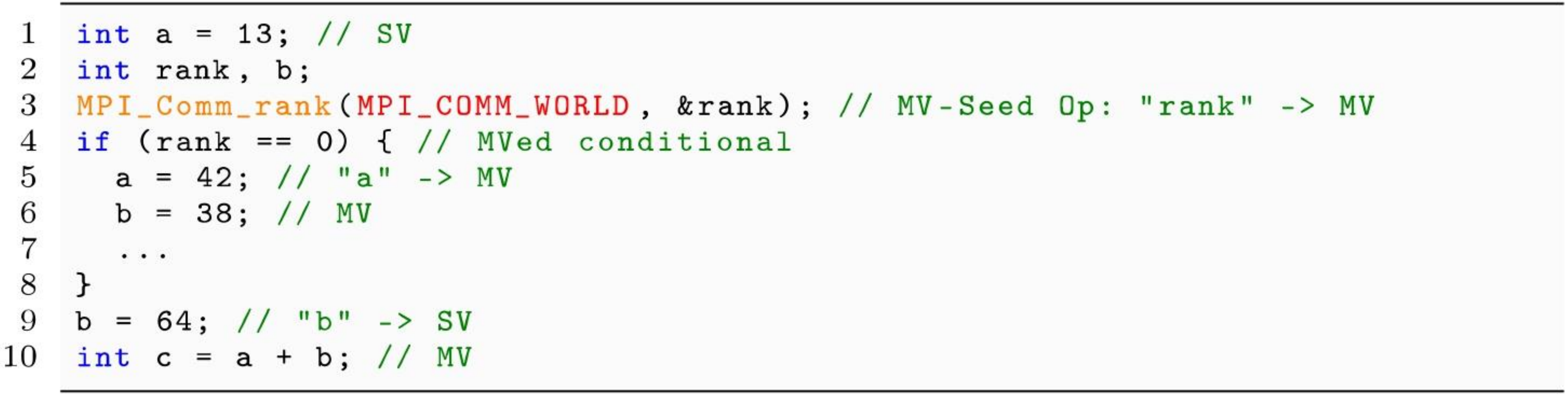

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- A variable or value is called multi-value (MV)
  - if its runtime-value may differ for a subset of processes
  - and called single-value (SV) otherwise
- MV-seed operations yield MVs per definition
- New MVs can result from operations using MVs
  - or through control-flow operations

SPMD IR: Extended Multi-Value Analysis

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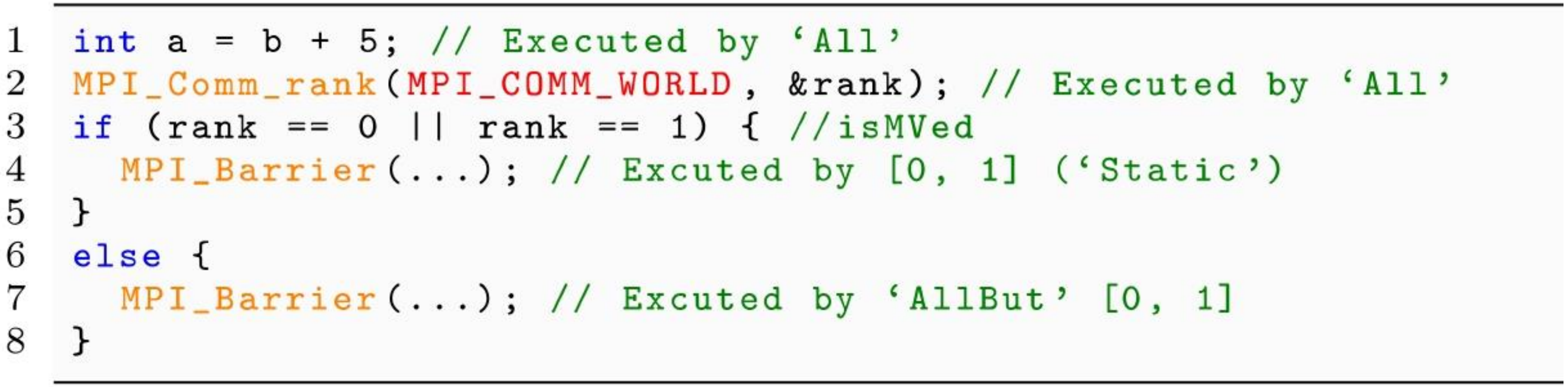

```
int a = b + 5; // Executed by ‘All’
MPI_Comm_rank(MPI_COMM_WORLD, &rank); // Executed by ‘All’
if (rank == 0 || rank == 1) { //isMVed
  MPI_Barrier(...); // Excuted by [0, 1] (‘Static’)
}
else {
  MPI_Barrier(...); // Excuted by ‘AllBut’ [0, 1]
}
```

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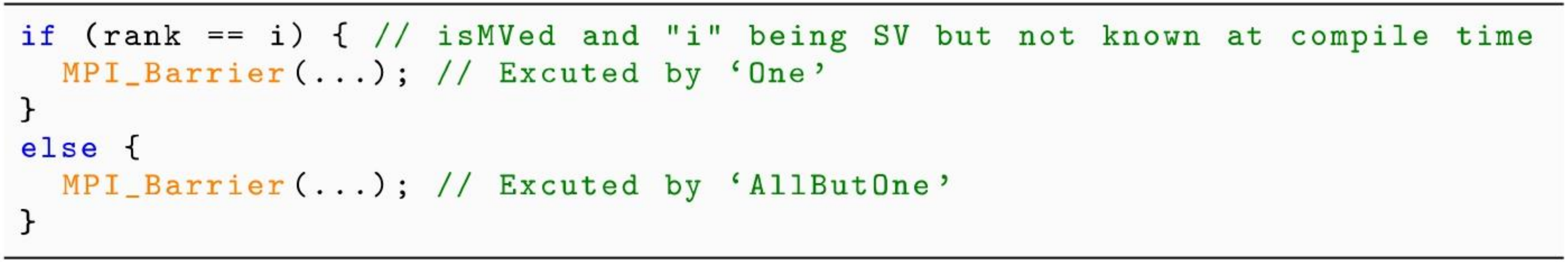

```
if (rank == i) { // isMVed and "i" being SV but not known at compile time
  MPI_Barrier(...); // Excuted by ‘One’
}
else {
  MPI_Barrier(...); // Excuted by ‘AllButOne’
}
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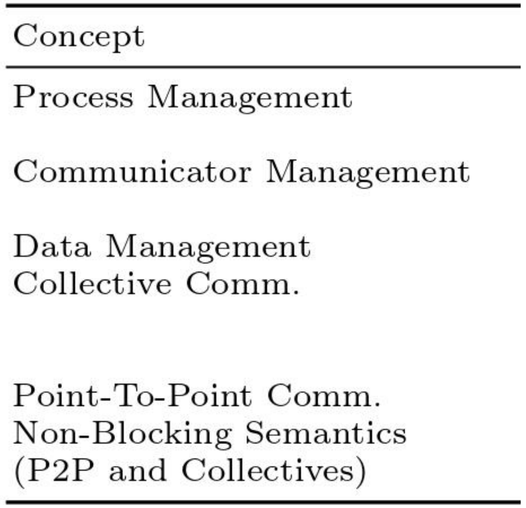
SPMD IR: Scope



Concept
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Communicator Management
Data Management
Collective Comm.
Point-To-Point Comm.
Non-Blocking Semantics (P2P and Collectives)

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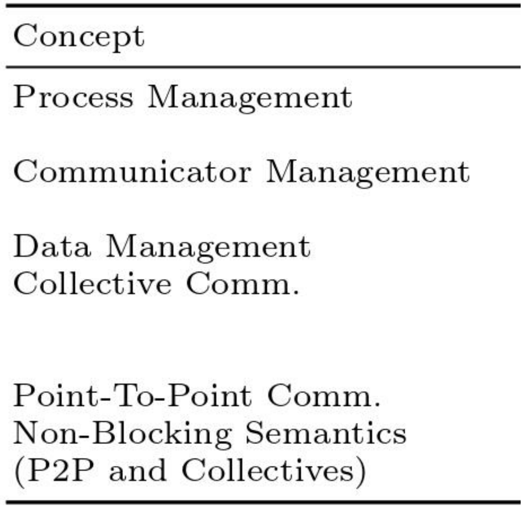

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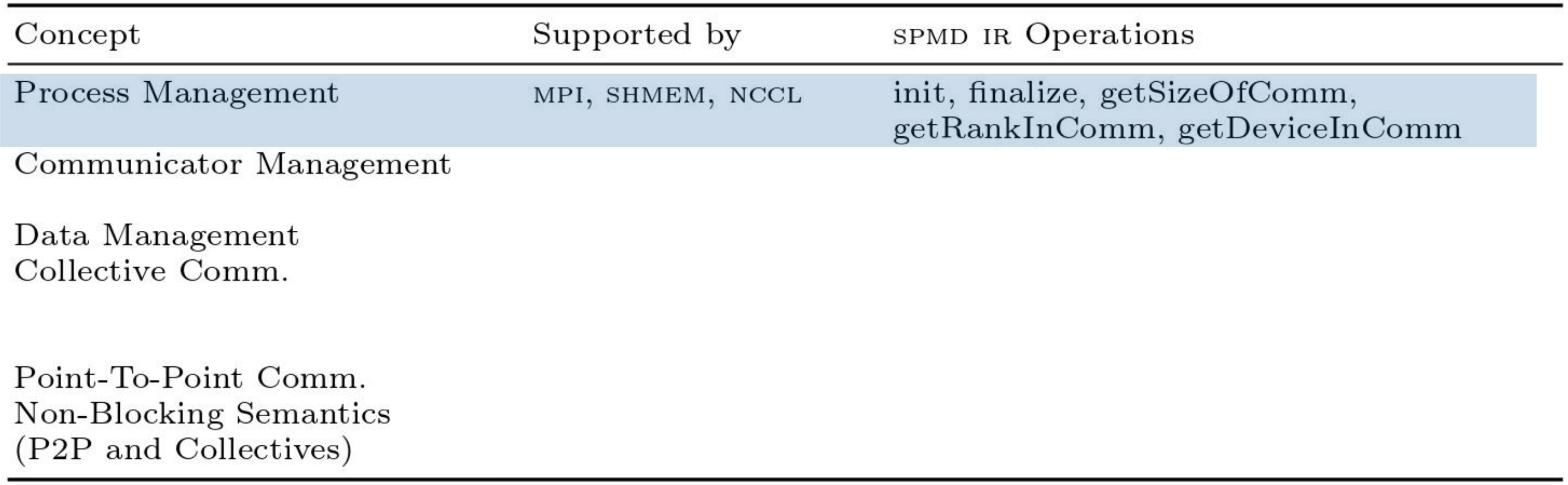

Concept	Supported by	SPMD IR Operations
Process Management	MPI, SHMEM, NCCL	init, finalize, getSizeOfComm, getRankInComm, getDeviceInComm
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Data Management		
Collective Comm.		
Point-To-Point Comm.		
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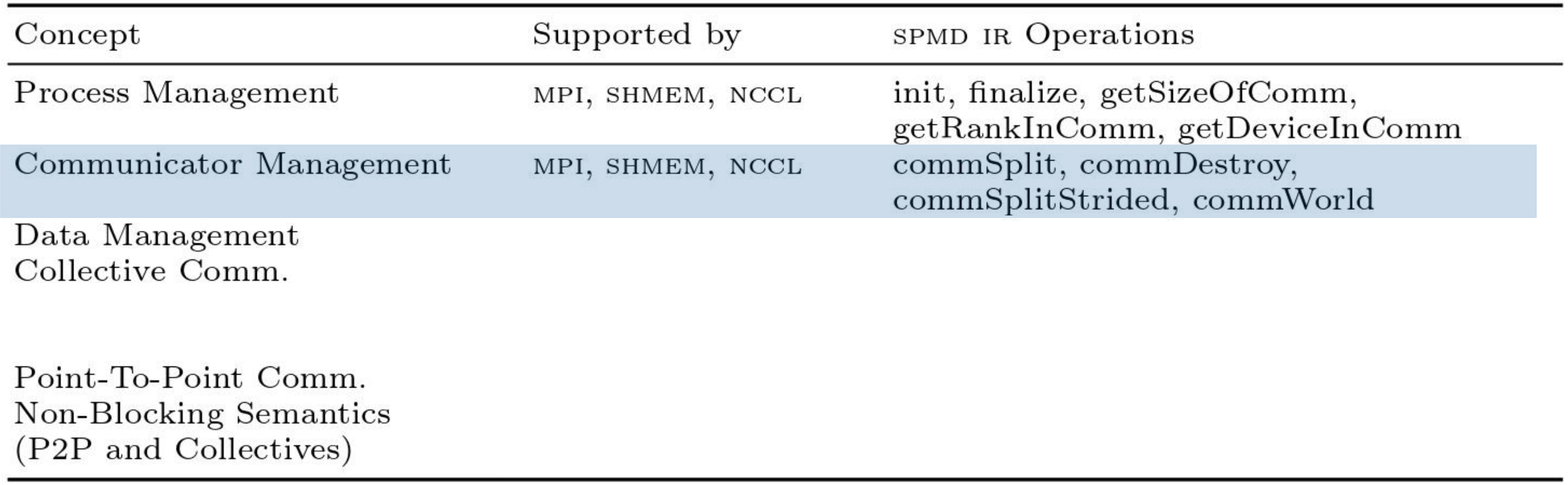

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Communicator Management	MPI, SHMEM, NCCL	commSplit, commDestroy, commSplitStrided, commWorld
Data Management		
Collective Comm.		
Point-To-Point Comm.		
Non-Blocking Semantics (P2P and Collectives)		

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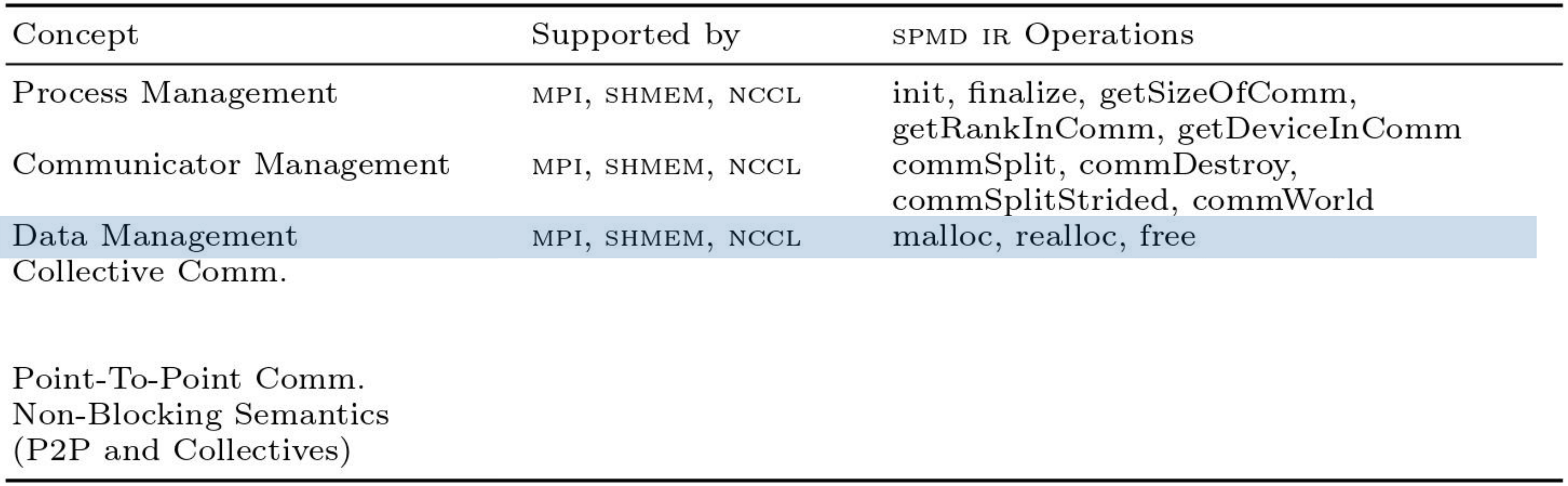

Concept	Supported by	SPMD IR Operations
Process Management	MPI, SHMEM, NCCL	init, finalize, getSizeOfComm, getRankInComm, getDeviceInComm
Communicator Management	MPI, SHMEM, NCCL	commSplit, commDestroy, commSplitStrided, commWorld
Data Management	MPI, SHMEM, NCCL	malloc, realloc, free
Collective Comm.		
Point-To-Point Comm.		
Non-Blocking Semantics (P2P and Collectives)		

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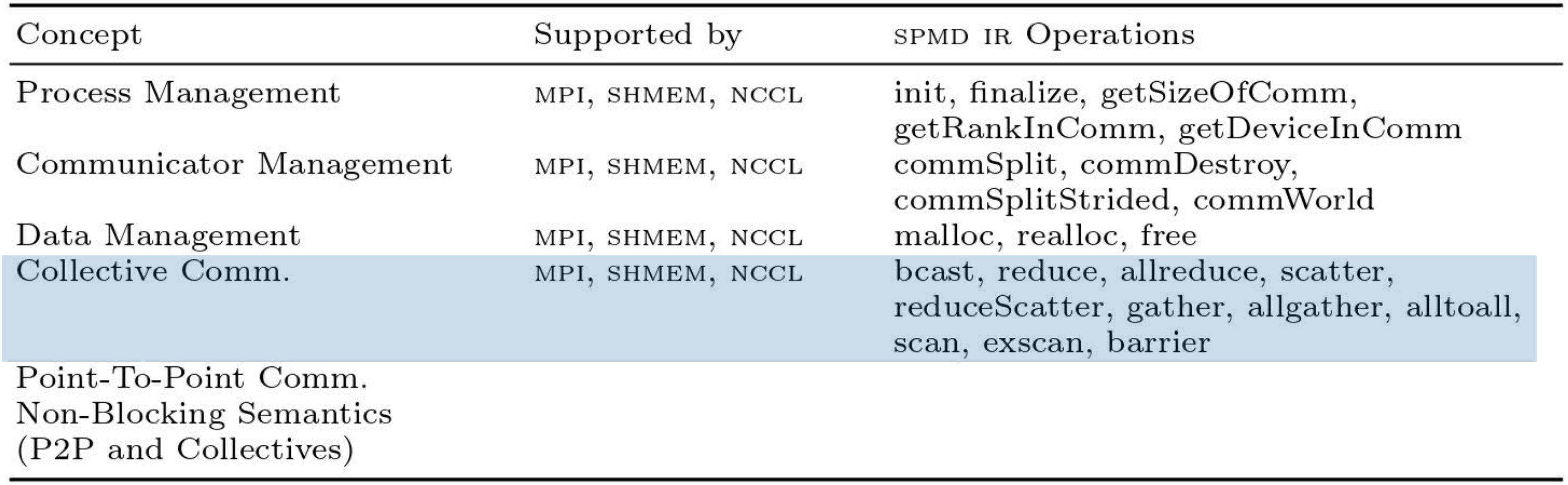

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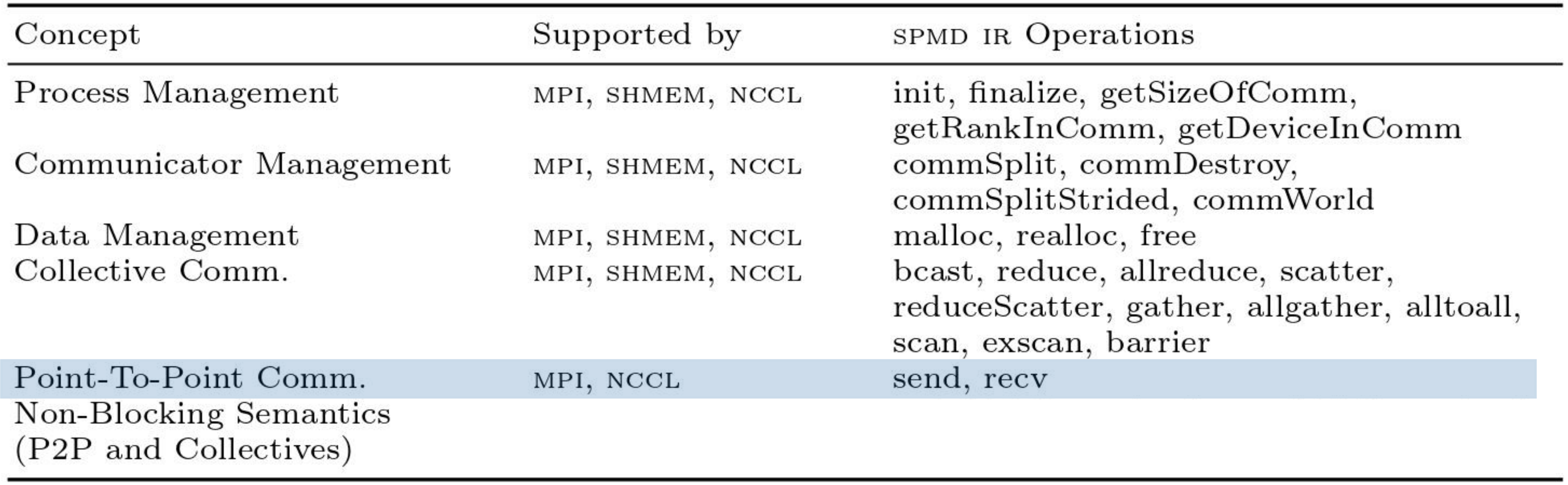

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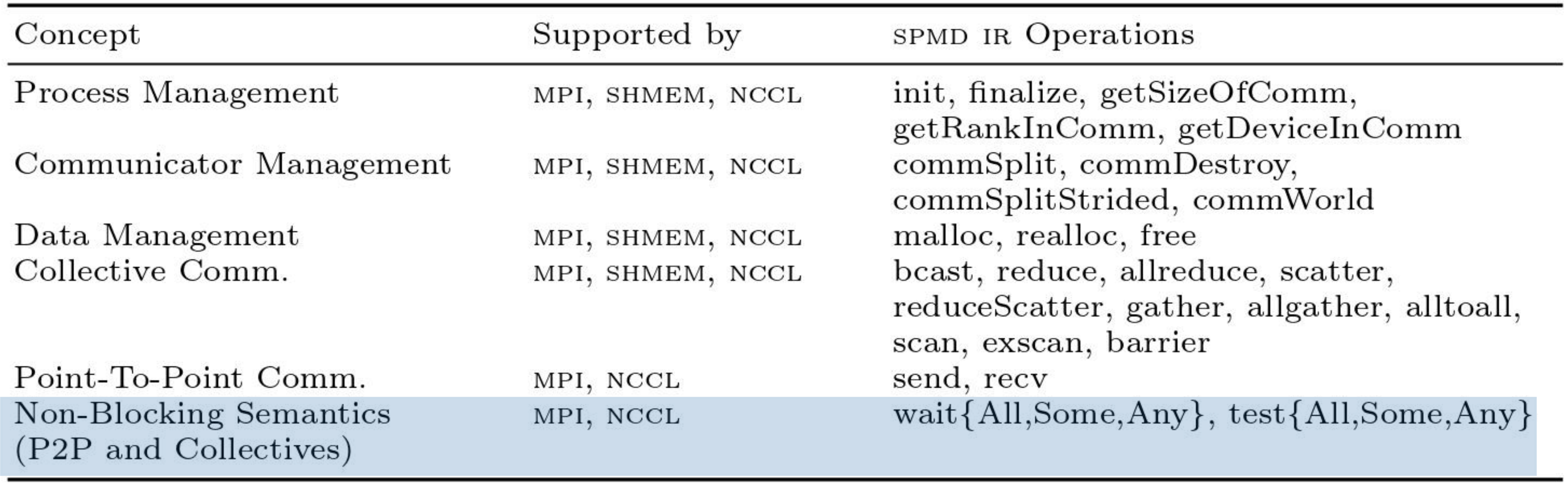

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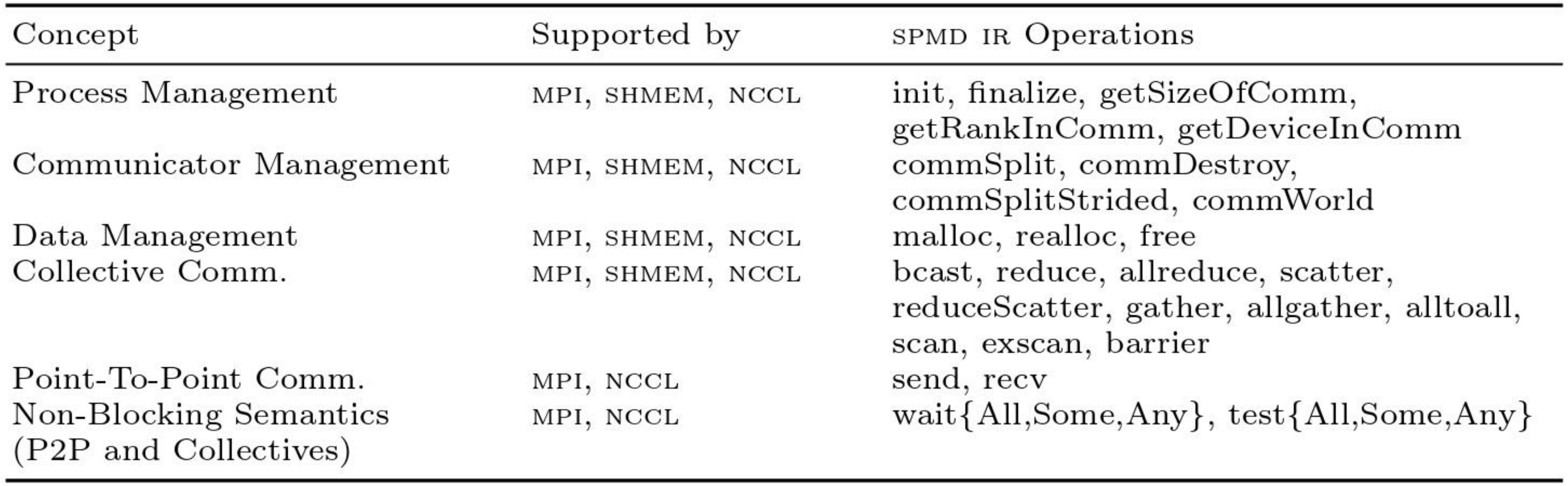

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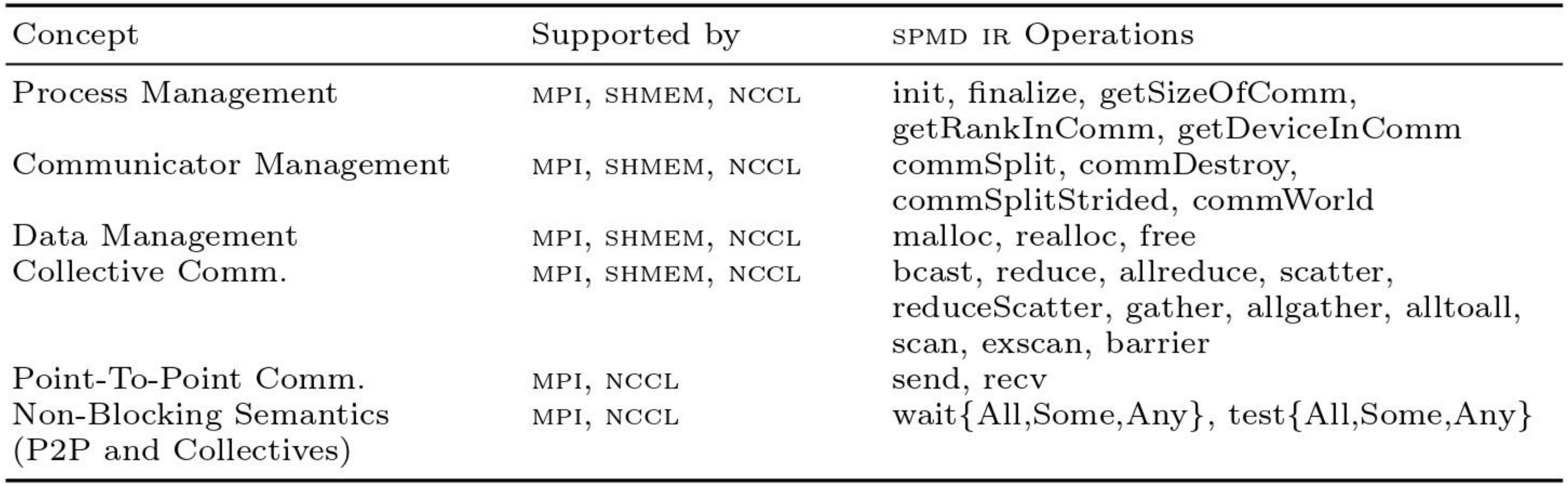
- Attributes for blocking or buffered communication

SPMD IR: Scope



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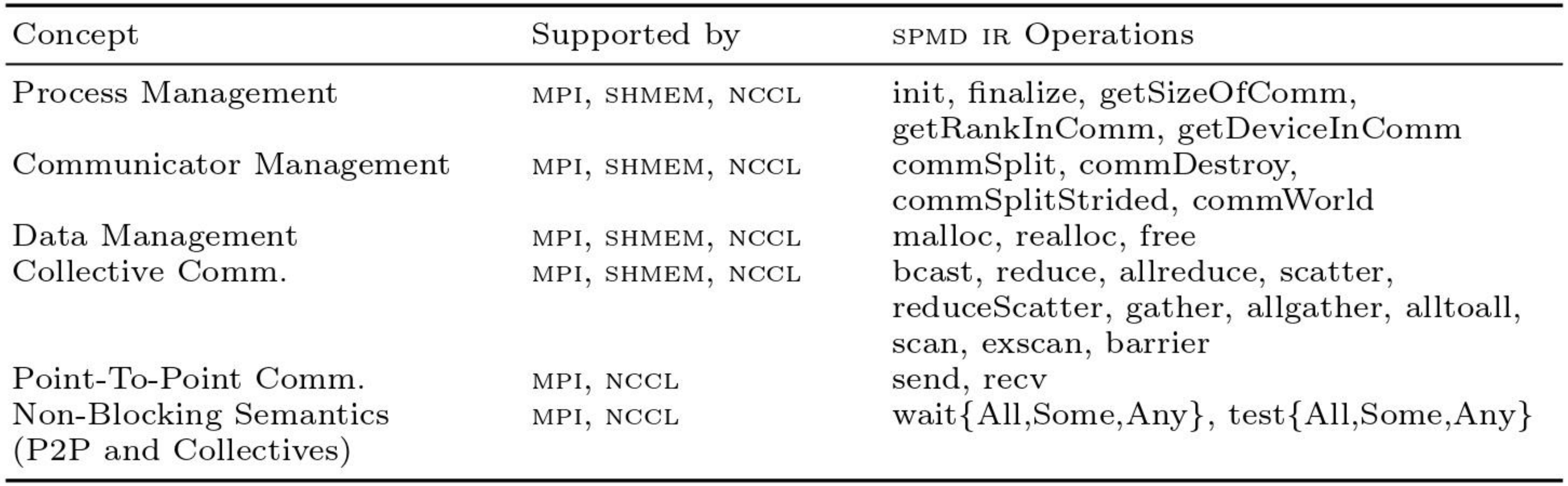

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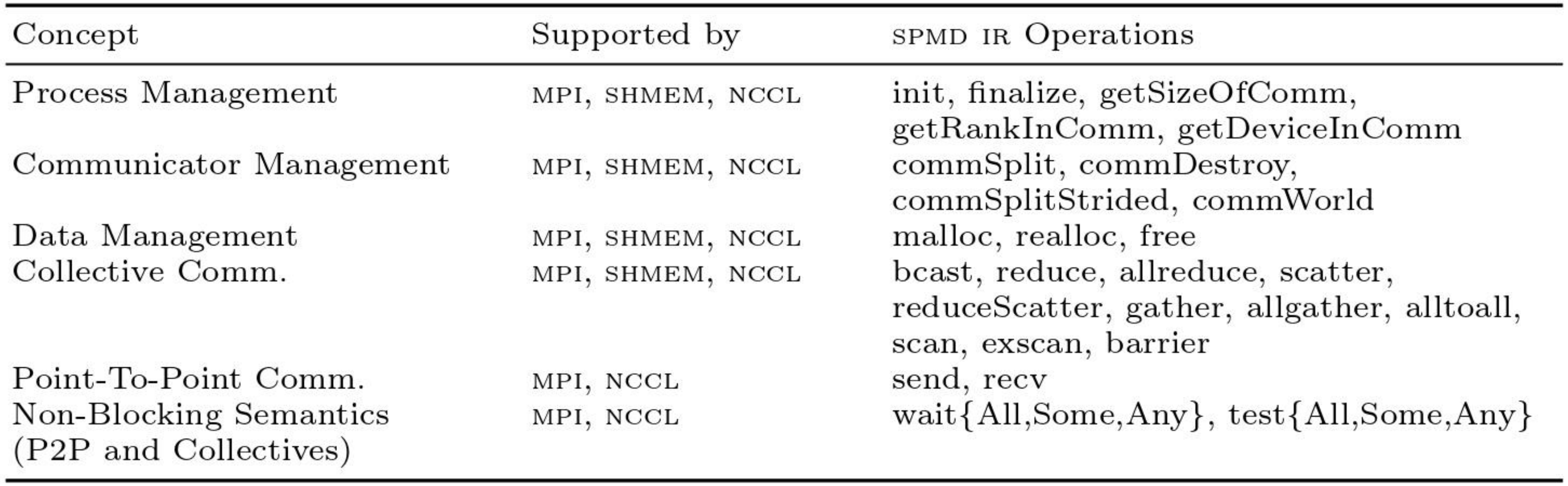

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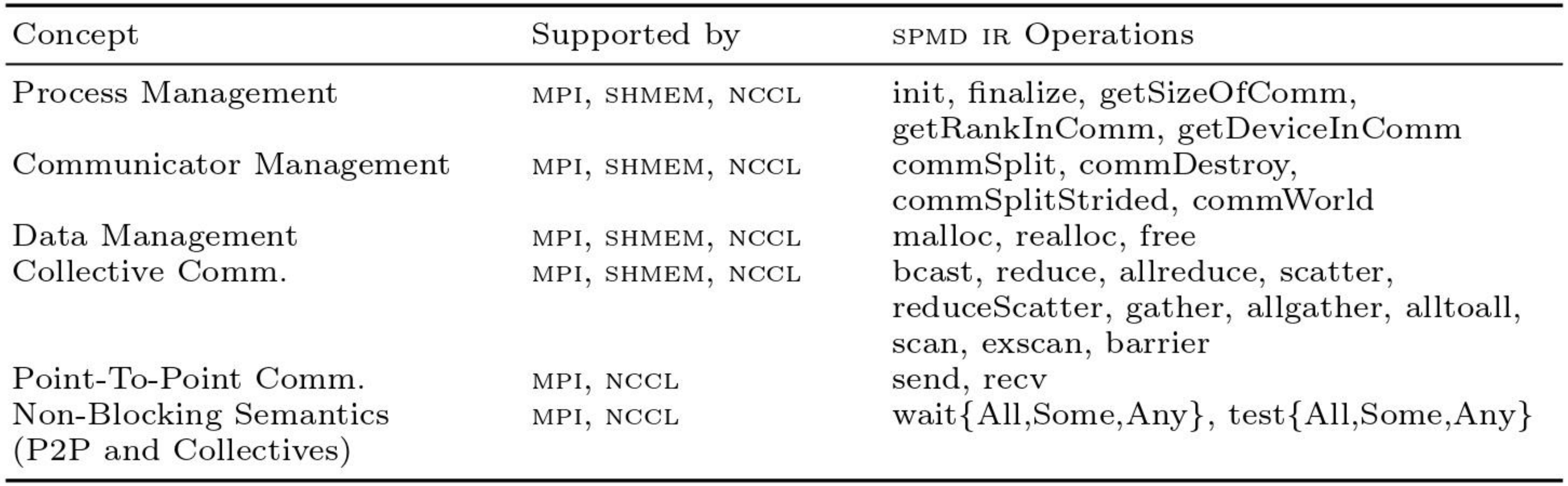

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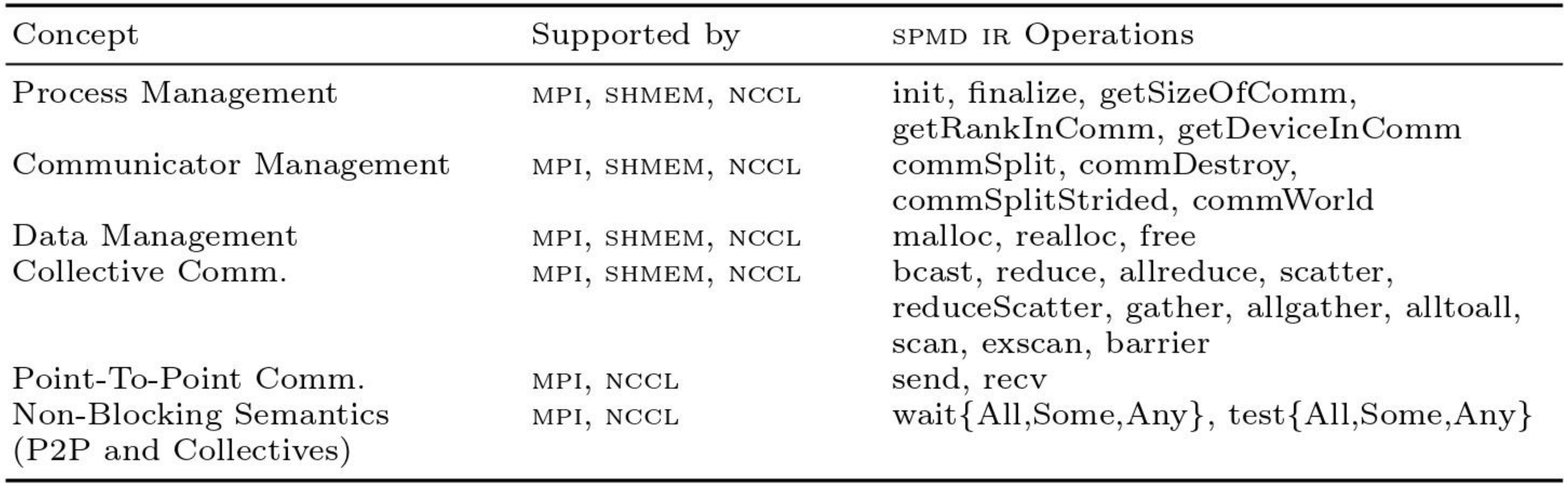

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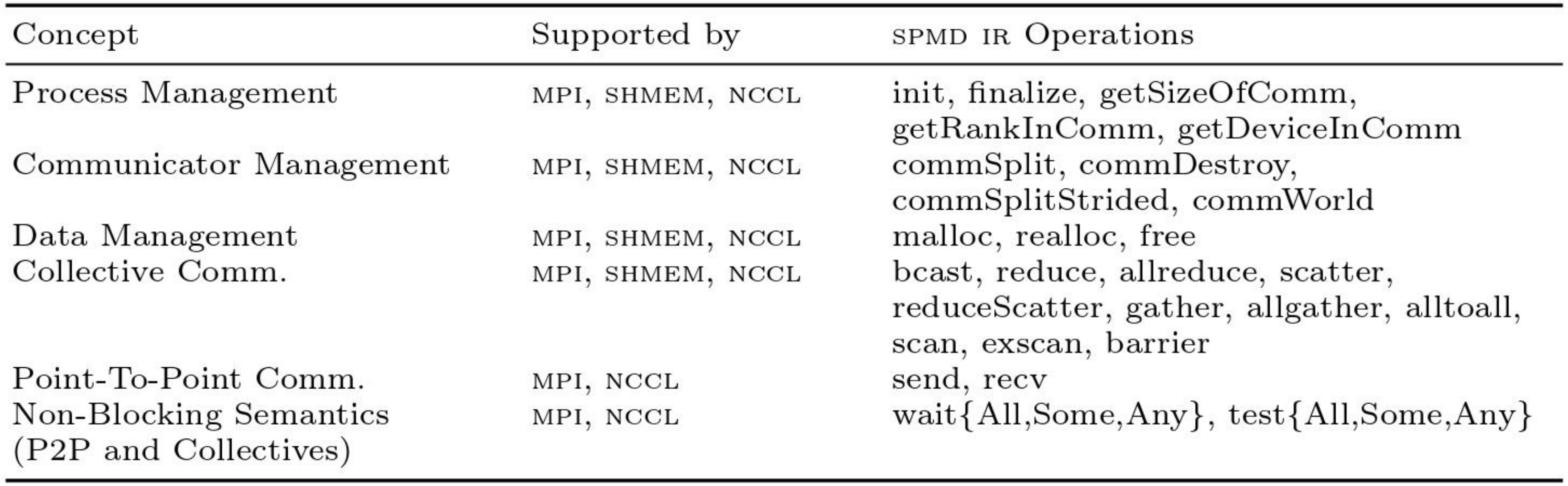

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- For memory references, IR specifies side-effects, e.g., read-only

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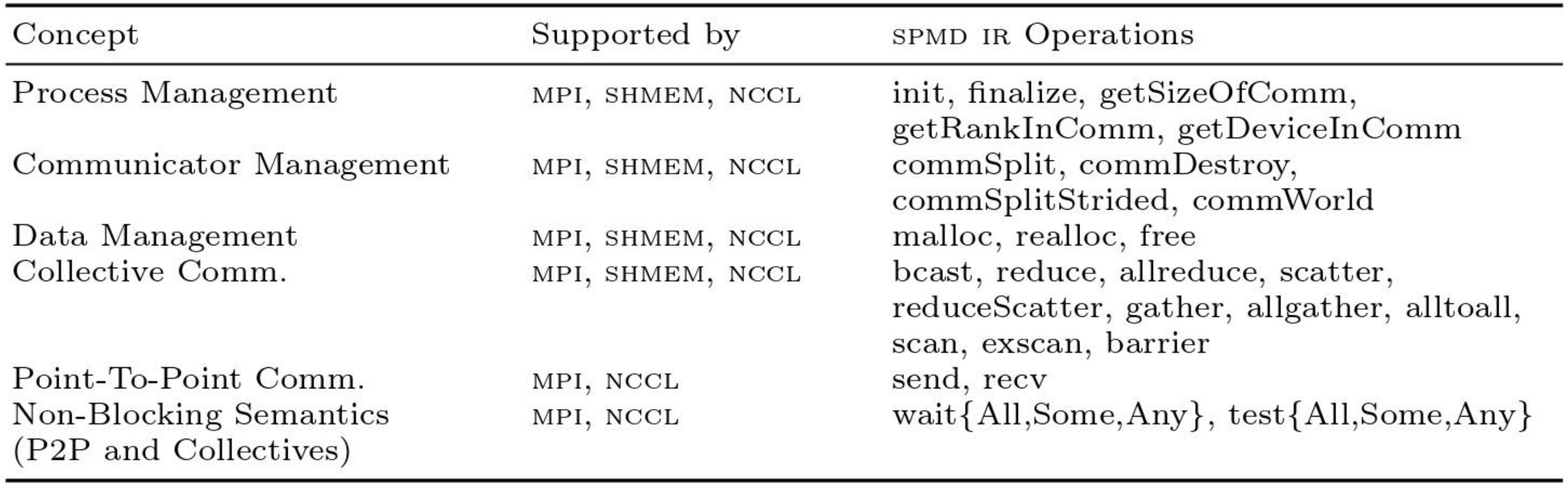

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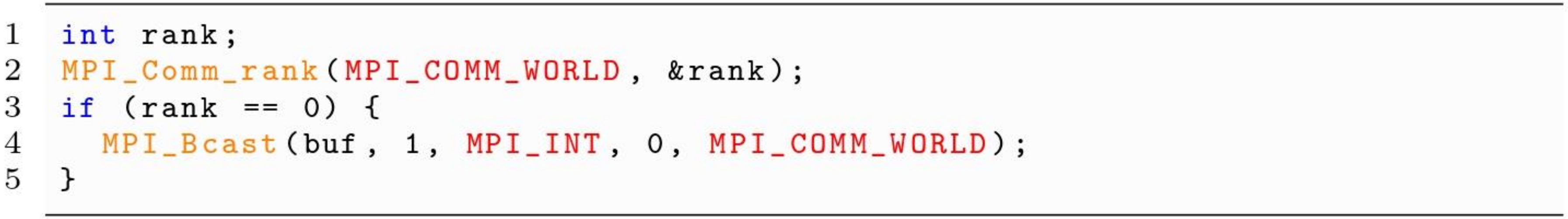
- For memory references, IR specifies side-effects, e.g., read-only

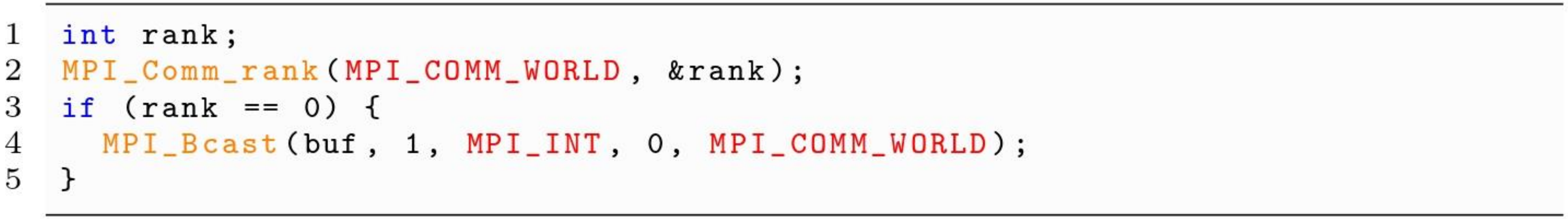
- RMA is work in progress

SPMD IR: Example



```
int rank;
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
if (rank == 0) {
  MPI_Bcast(buf, 1, MPI_INT, 0, MPI_COMM_WORLD);
}
```

SPMD IR: Example



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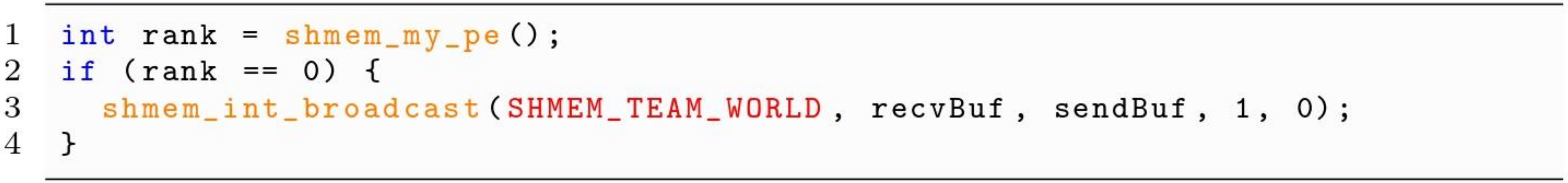

```
int rank = shmem_my_pe();
if (rank == 0) {
  shmem_int_broadcast(SHMEM_TEAM_WORLD, recvBuf, sendBuf, 1, 0);
}
```

SPMD IR: Example

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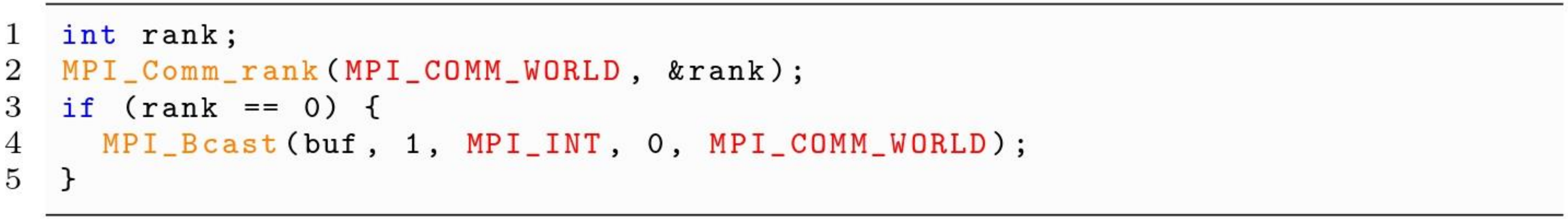
```

```
%rank, %error1 = spmd.getRankInComm(%comm)

%cmpRes = arith.cmpi eq (%rank, %c0)
scf.if (%cmpRes) {
  %error2 = spmd.bcast (%comm, %sendBuf, %recvBuf, %count, %i32Type, %c0)


}
```

SPMD IR: Example



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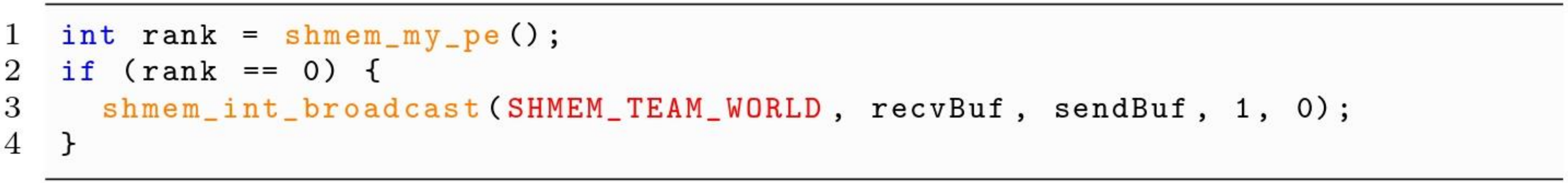

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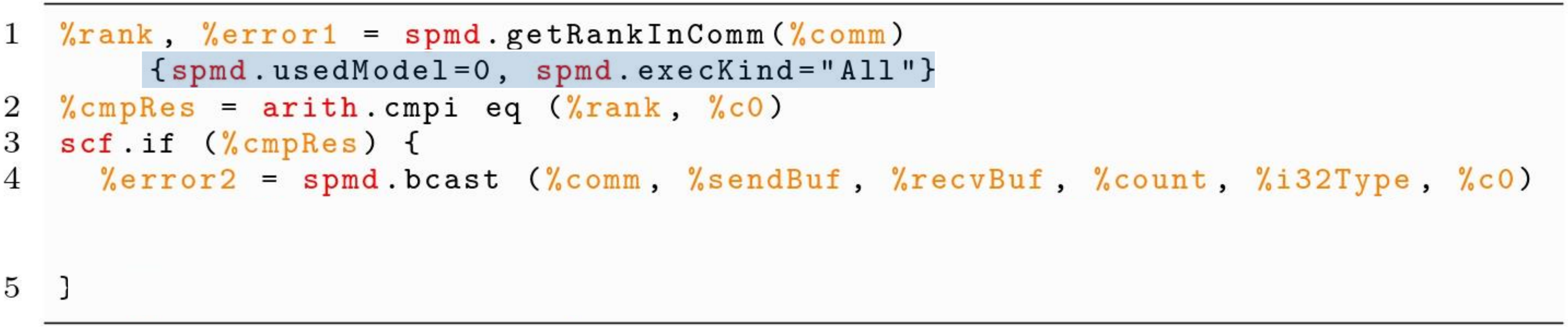

```
%rank, %error1 = spmd.getRankInComm(%comm)
      {spmd.usedModel=0, spmd.execKind="All"}
%cmpRes = arith.cmpi eq (%rank, %c0)
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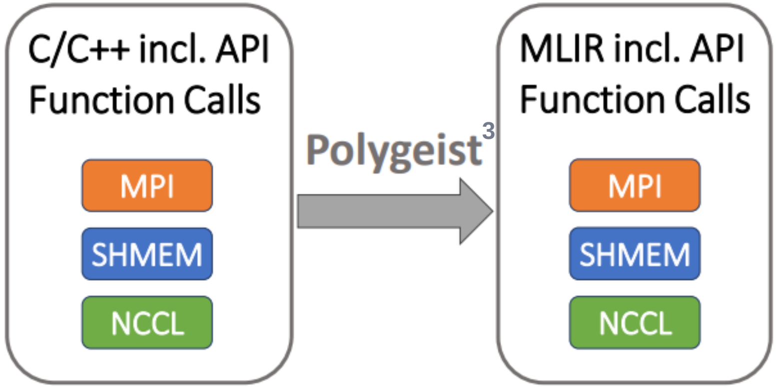
       spmd.execKind="Static"}
} {spmd.execKind="All", spmd.isMV=true}
```

SPMD IR: Workflow

[3] Moses et al.: Polygeist: Raising C to Polyhedral MLIR. PACT ’21



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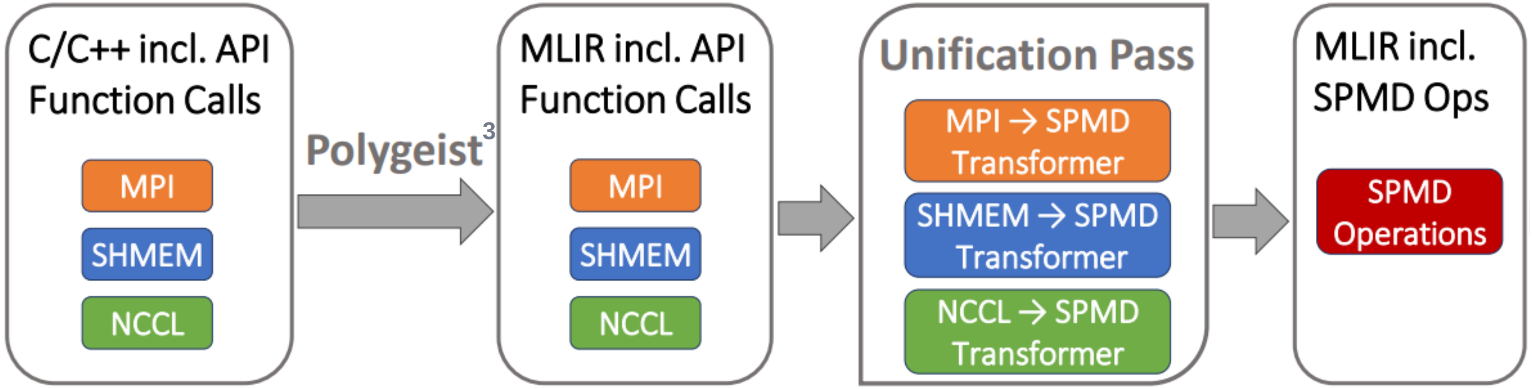

C/C++ incl. API Function Calls
- MPI
- SHMEM
- NCCL

Polygeist[3]

MLIR incl. API Function Calls
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Unification Pass
- MPI → SPMD Transformer
- SHMEM → SPMD Transformer
- NCCL → SPMD Transformer

MLIR incl. SPMD Ops
- SPMD Operations

SPMD IR: Workflow

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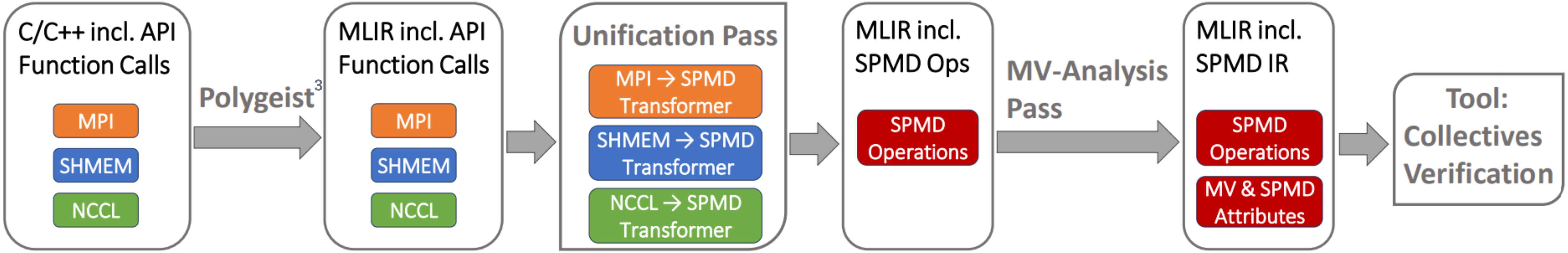

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Polygeist[3]

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- NCCL → SPMD Transformer

MLIR incl. SPMD Ops
- SPMD Operations

MV-Analysis Pass

MLIR incl. SPMD IR
- SPMD Operations
- MV & SPMD Attributes

Tool: Collectives Verification

[4] Huchant et al: Multi-Valued Expression Analysis for Collective Checking. Euro-Par ’19
[5] Huchant et al: PARCOACH Extension for a Full-Interprocedural Collectives Verification. Correctness ‘18

Evaluation

- Use case: static verification of collective communiation
  - The same kind of collectives has to be called in order by all processes of the same comm.

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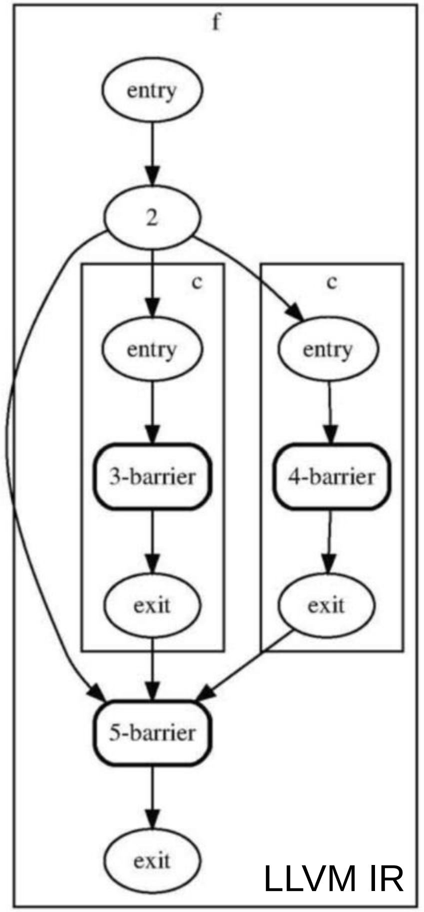

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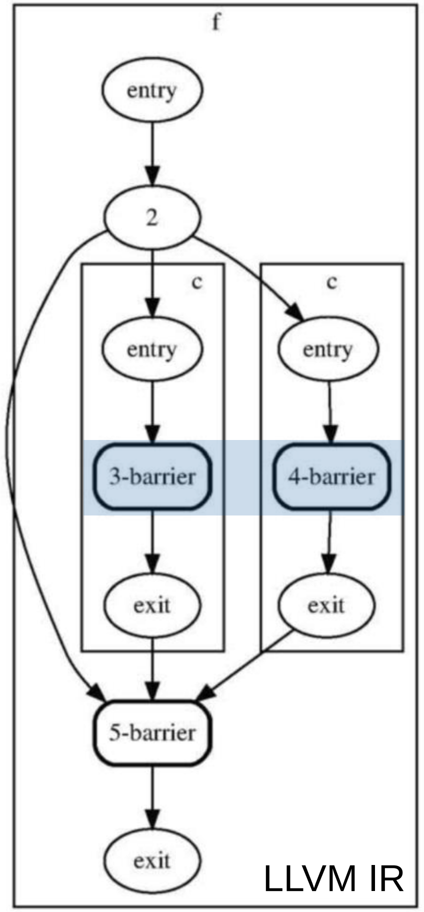

[5]

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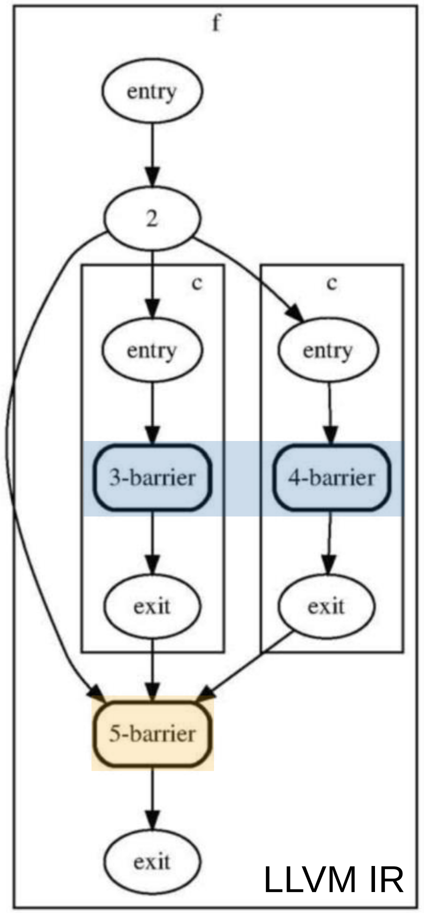

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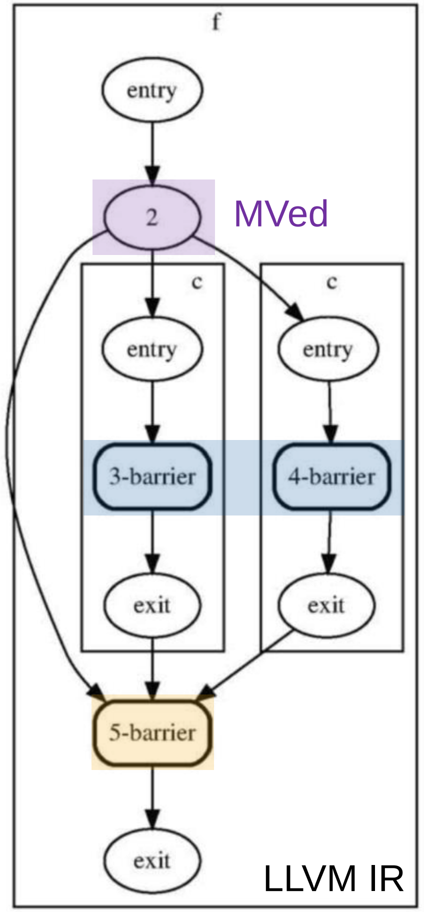

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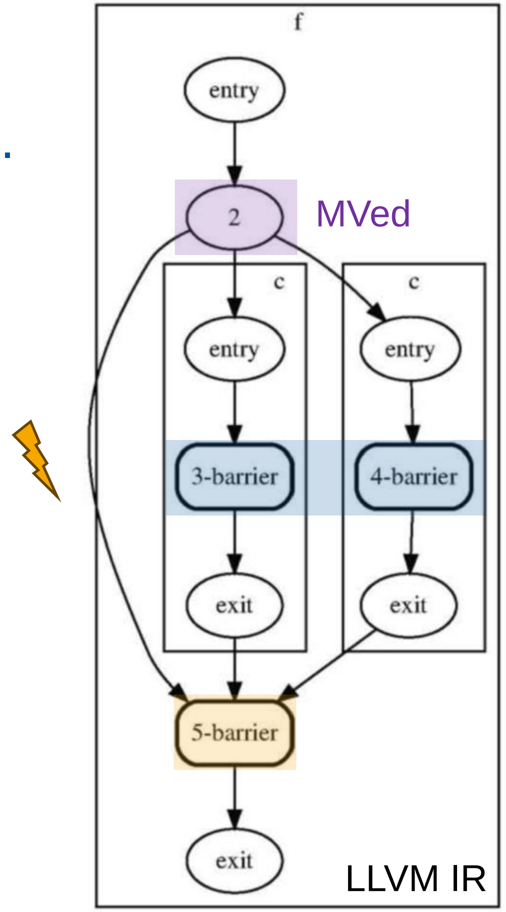

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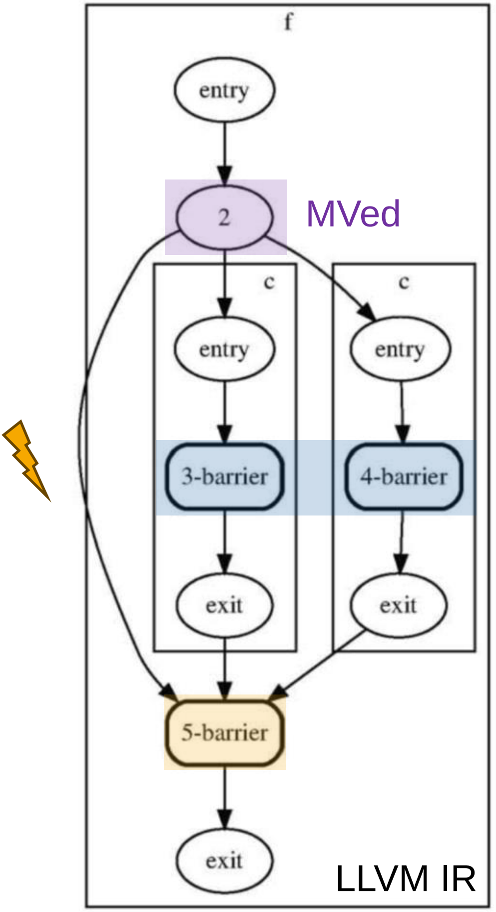

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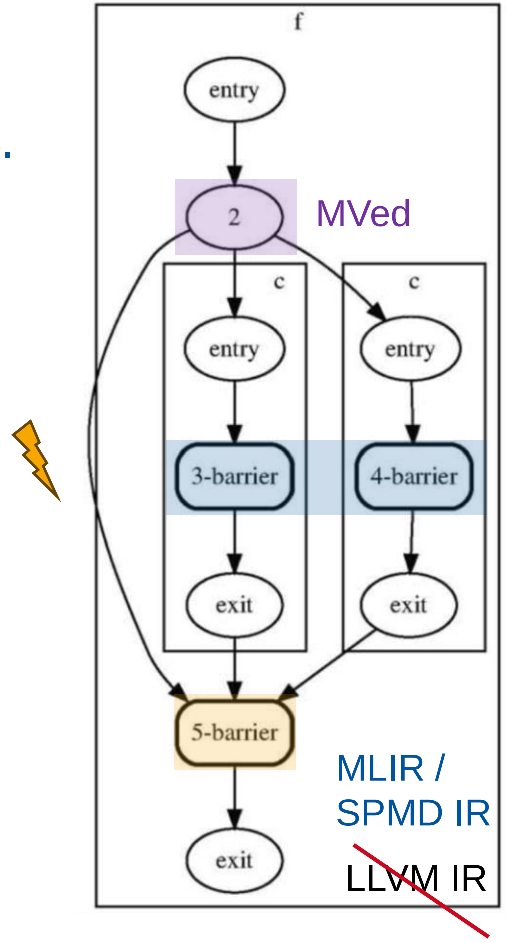

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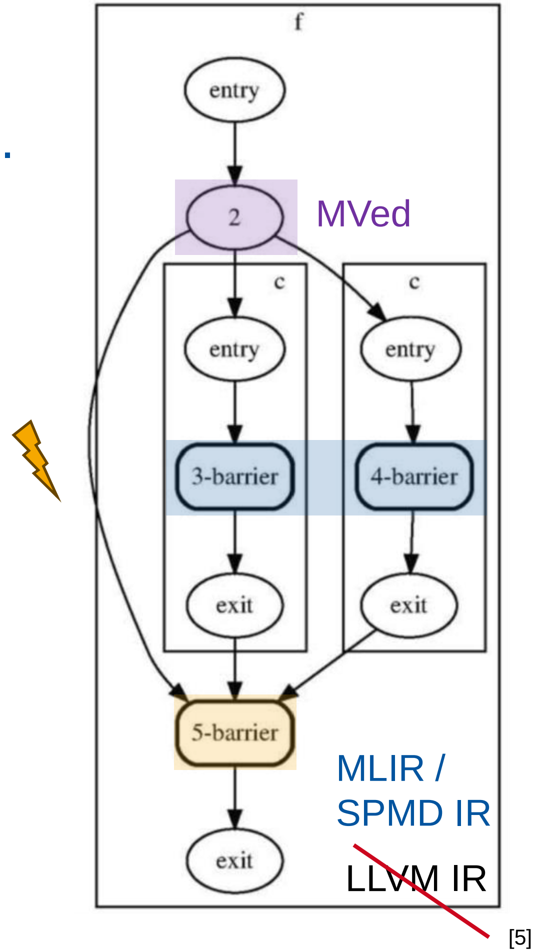

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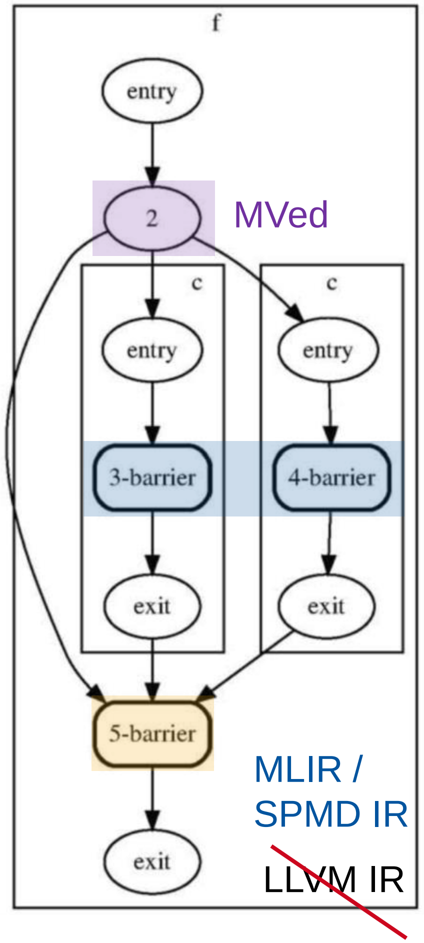

MVed

MLIR /
SPMD IR

~~LLVM IR~~

[5]

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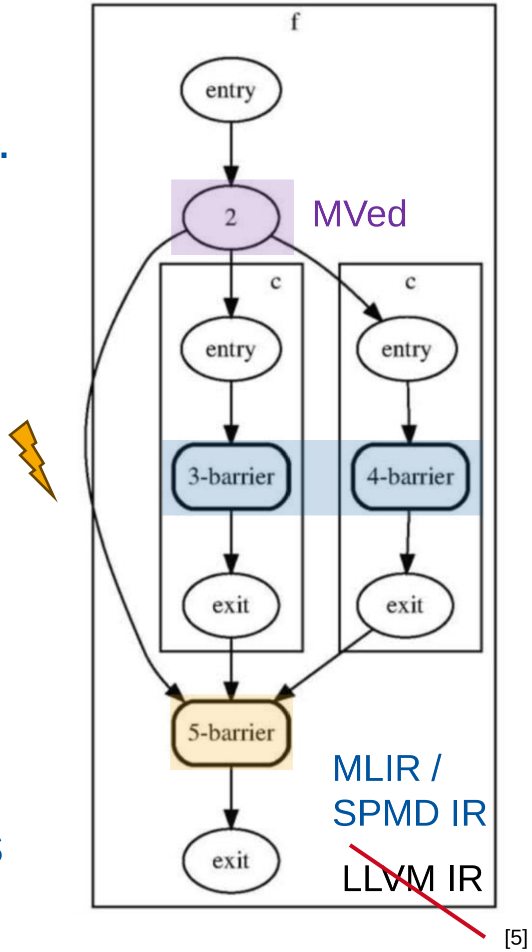
- Assessment based on PARCOACH‘s micro-benchmark suite and custom test cases
  - Port original MPI codes to SHMEM and NCCL and provide hybrid cases



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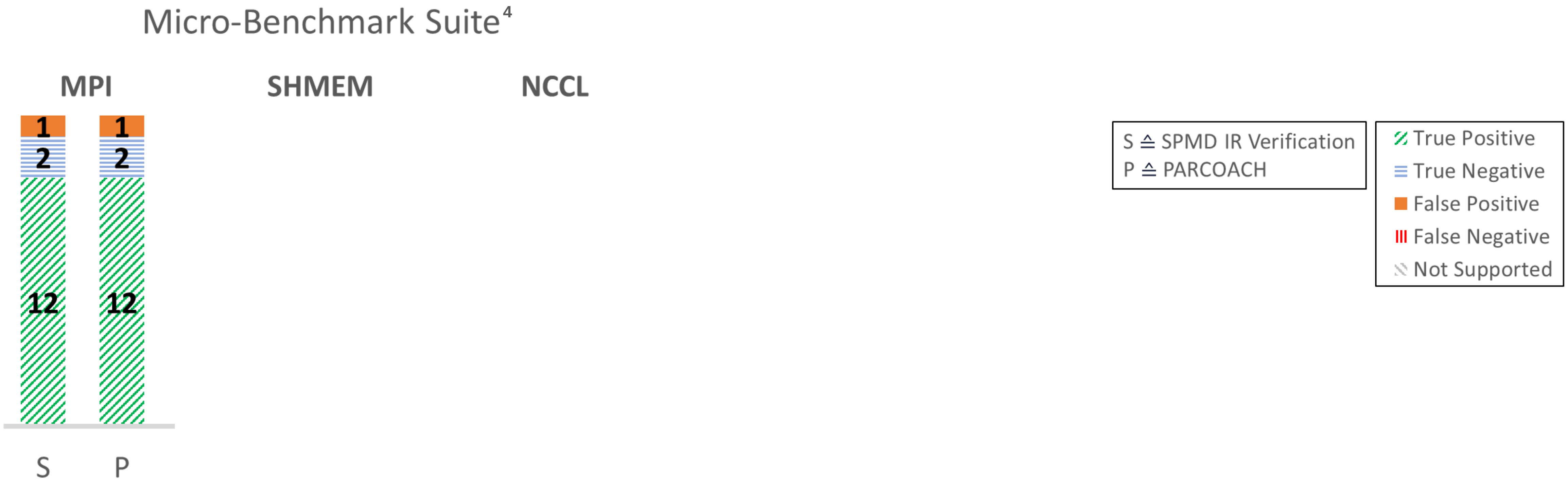

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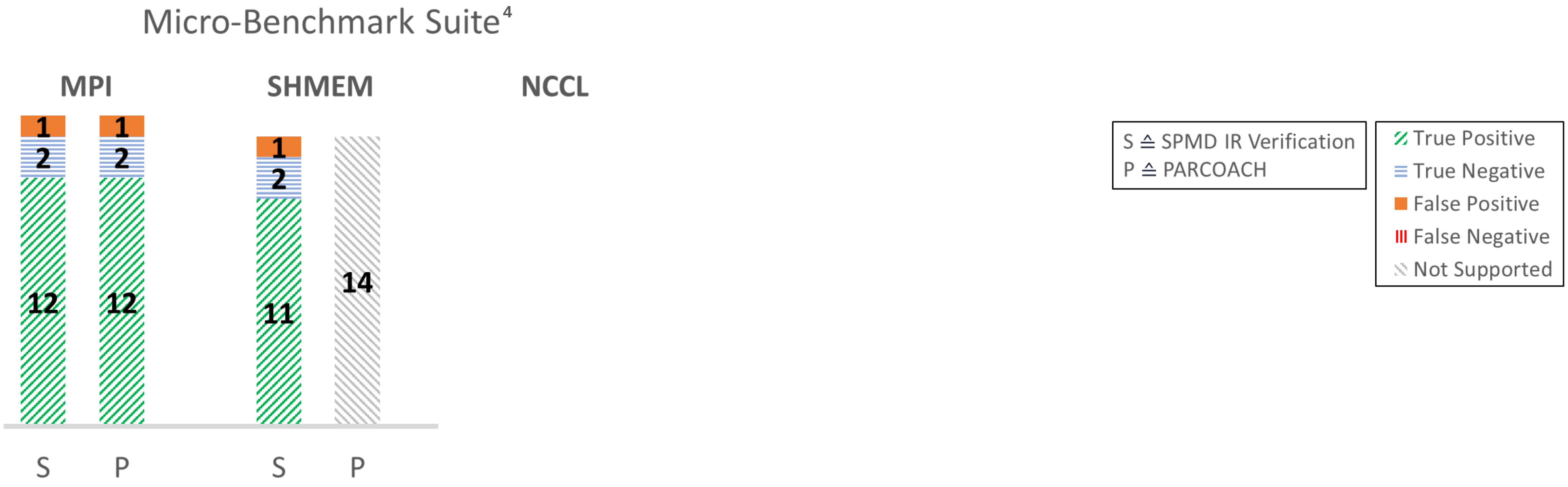

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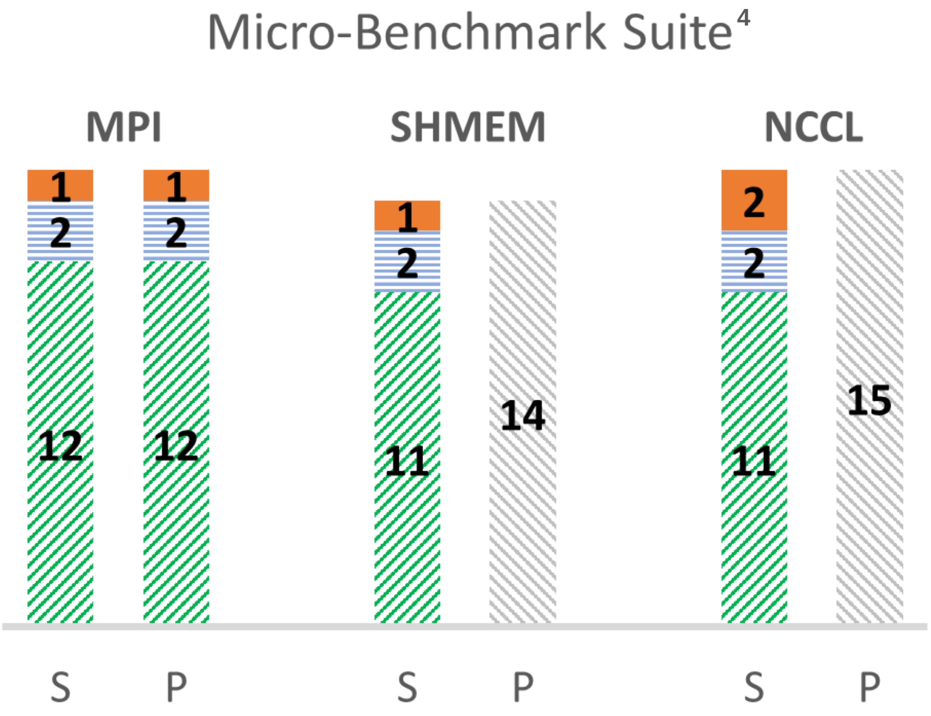

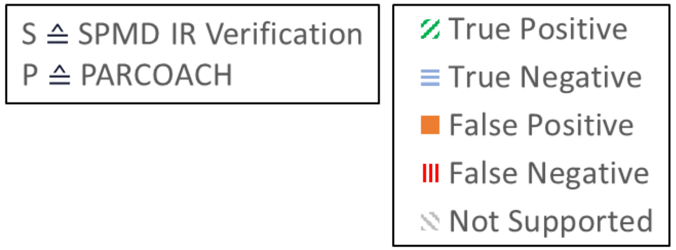

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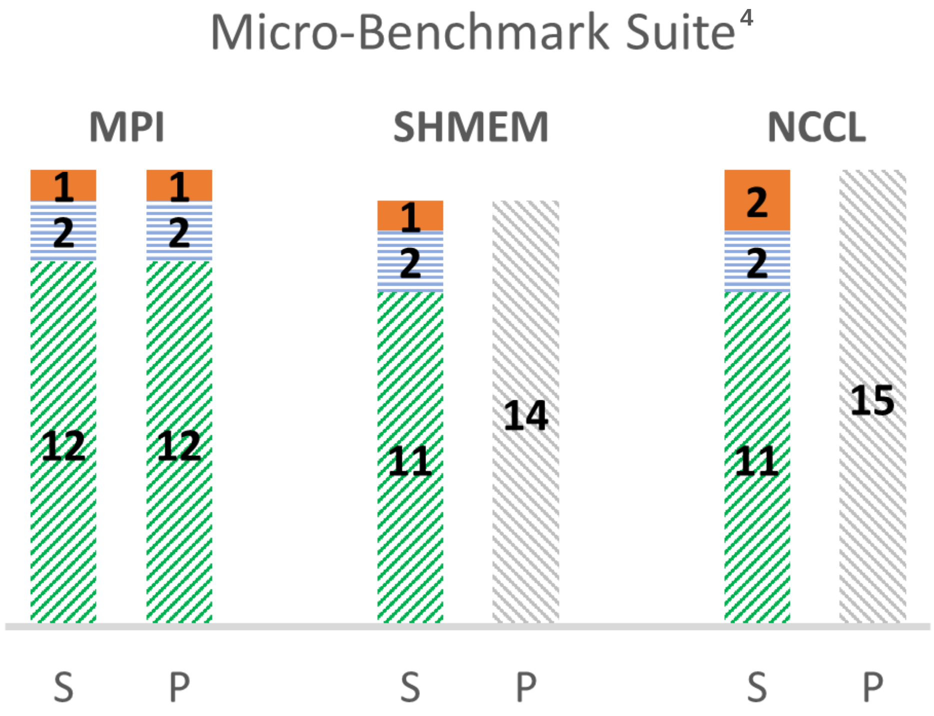
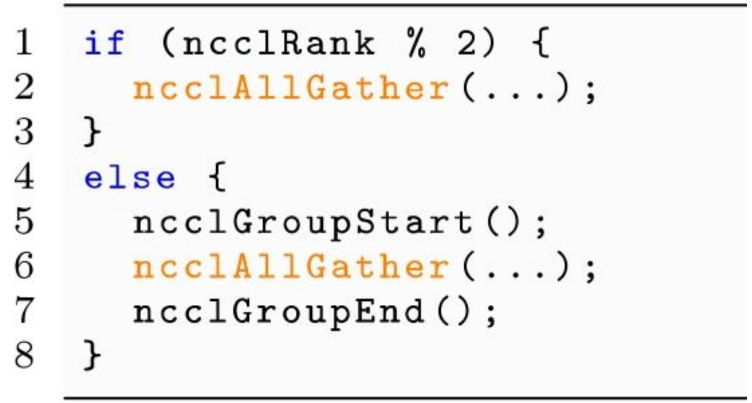


S ≙ SPMD IR Verification
P ≙ PARCOACH

▨ True Positive
≡ True Negative
■ False Positive
Ⅲ False Negative
▨ Not Supported



```
if (ncclRank % 2) {
  ncclAllGather(...);
}
else {
  ncclGroupStart();
  ncclAllGather(...);
  ncclGroupEnd();
}
```

Evaluation: Results

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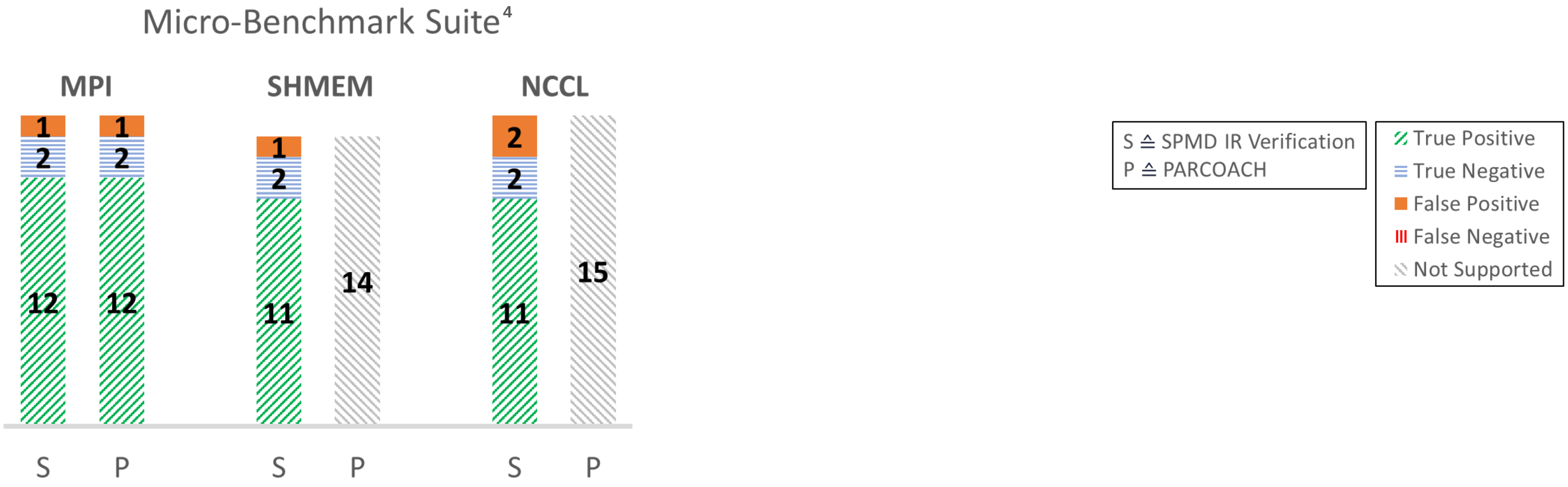
Micro-Benchmark Suite[4]

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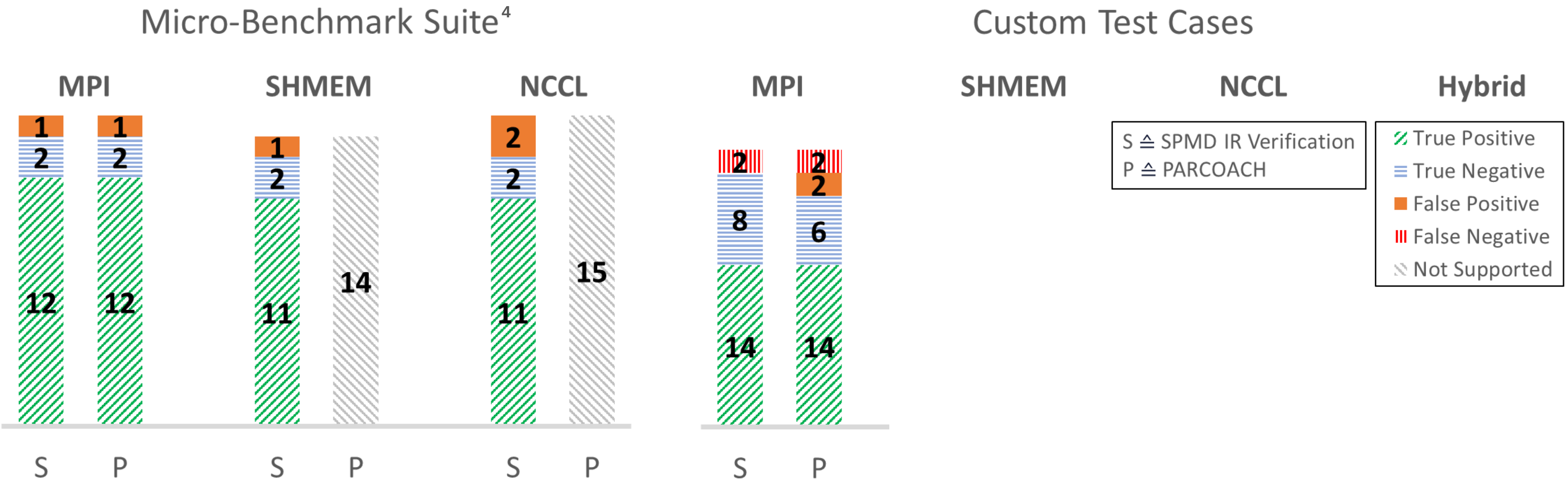

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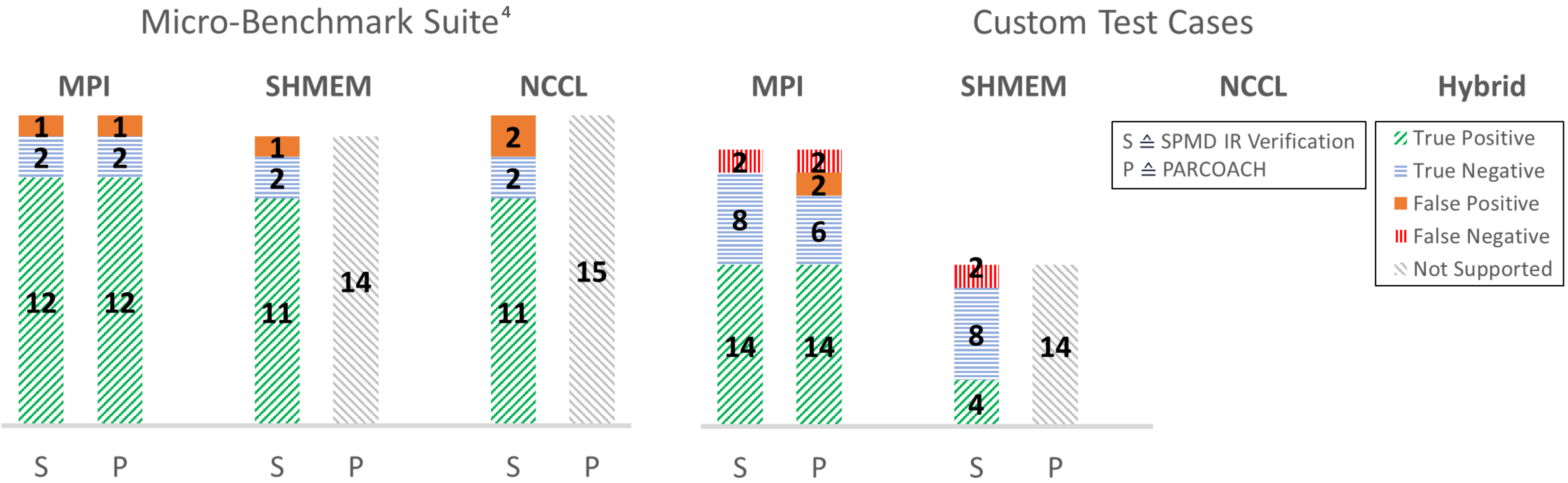

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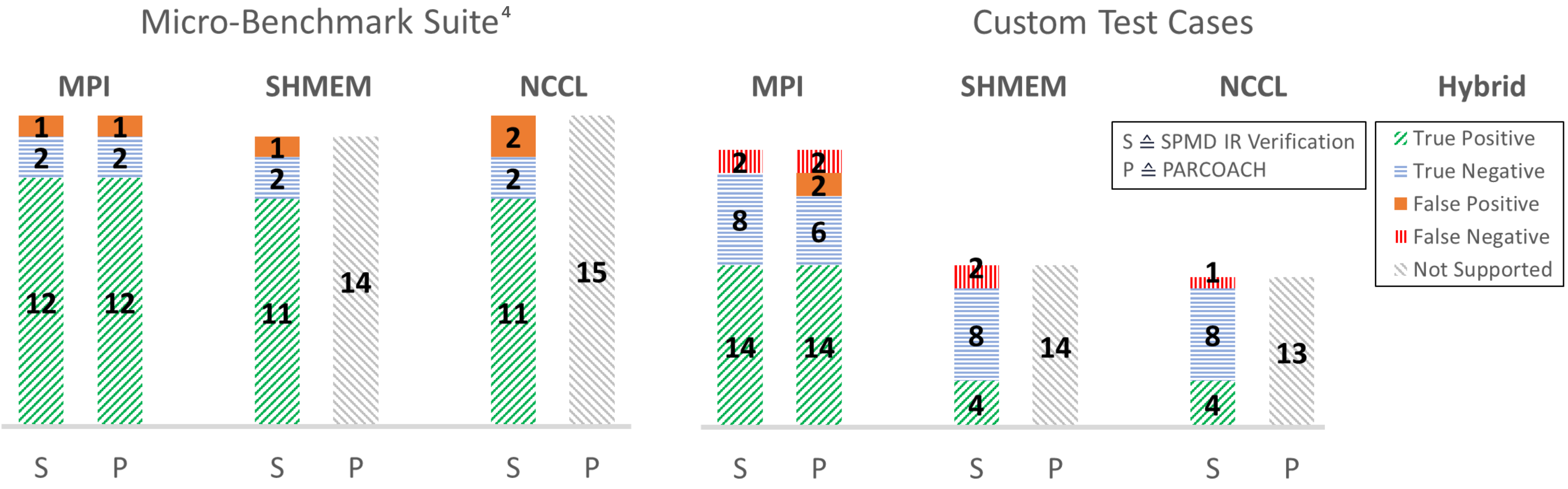

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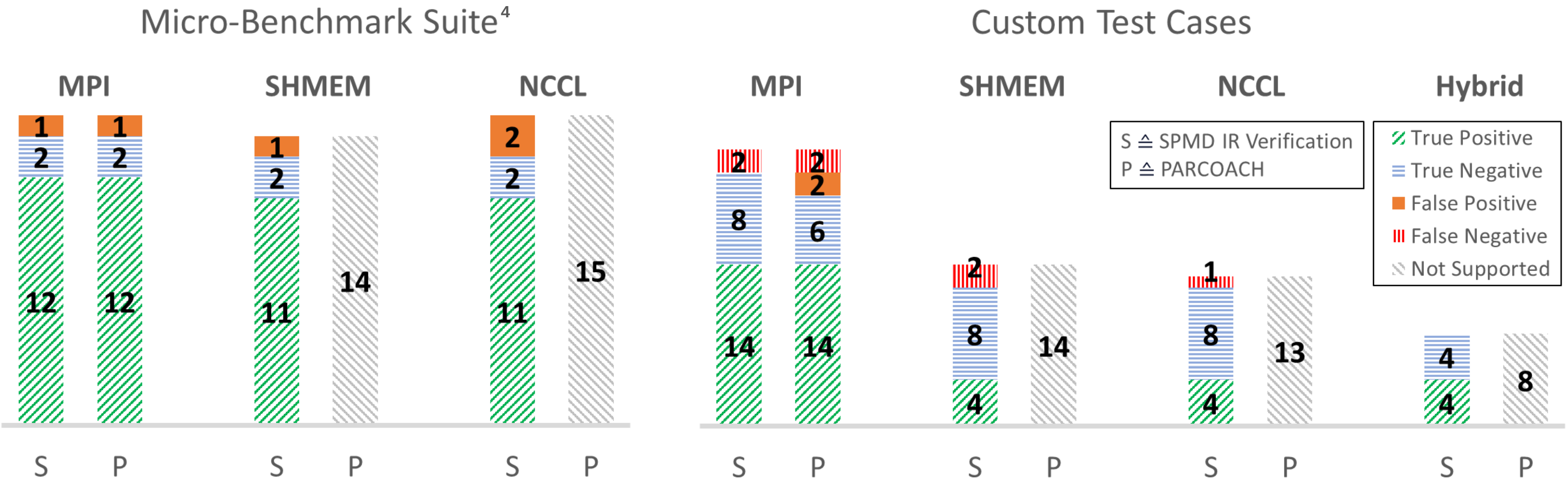

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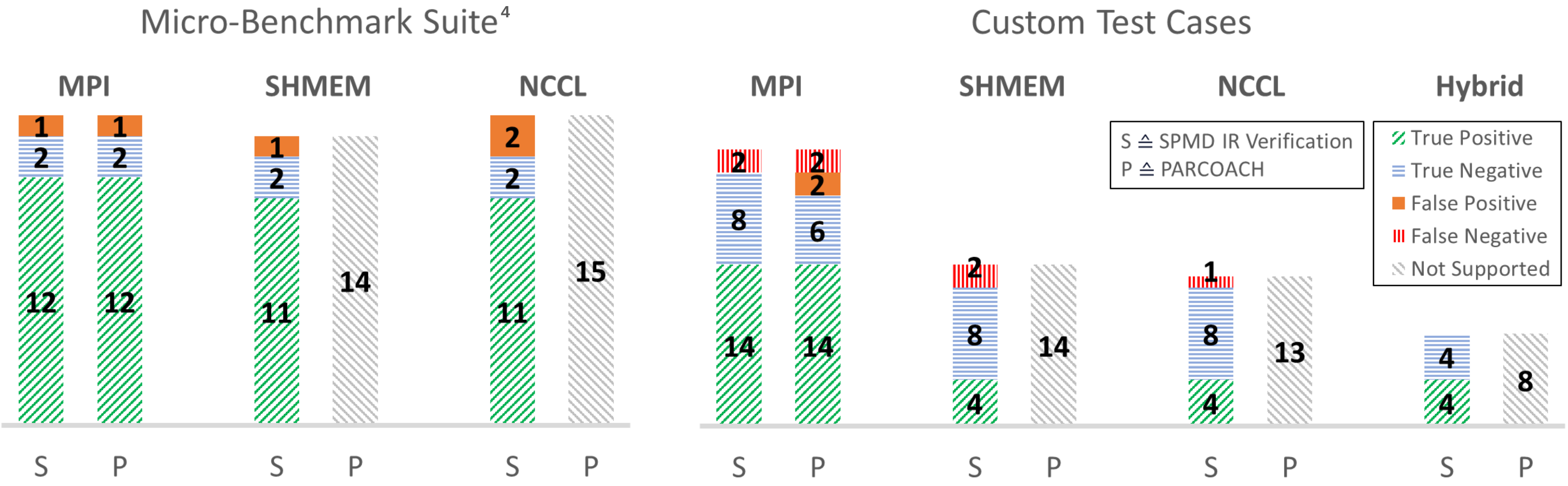

- SPMD IR
  - covers two test cases correctly, where PARCOACH fails

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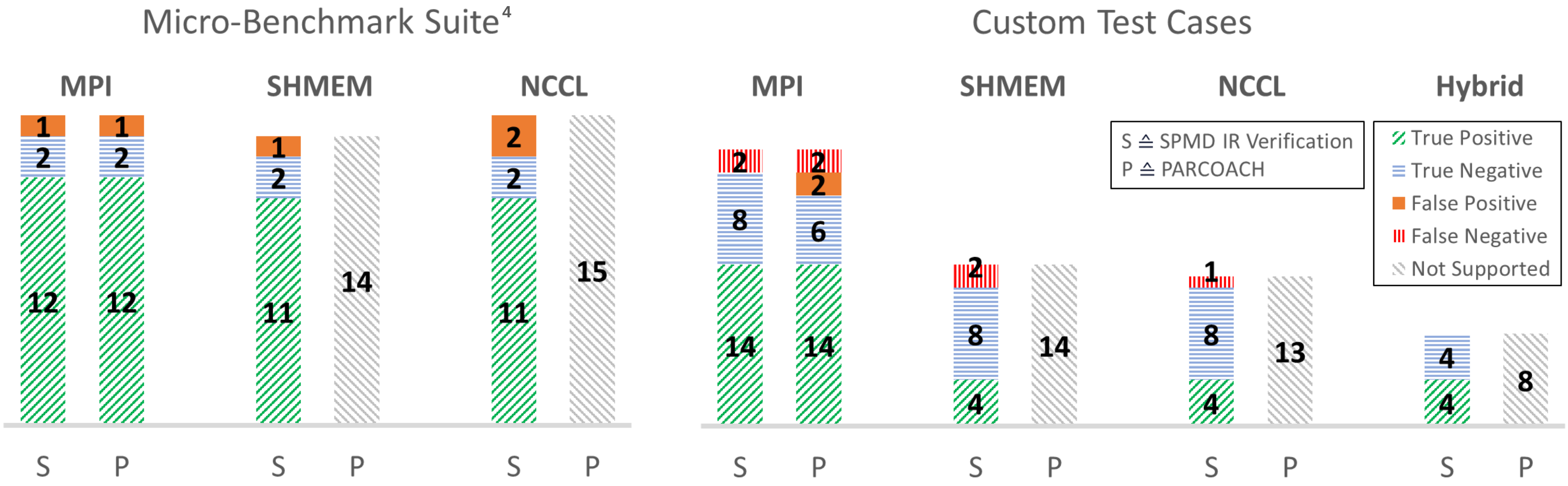

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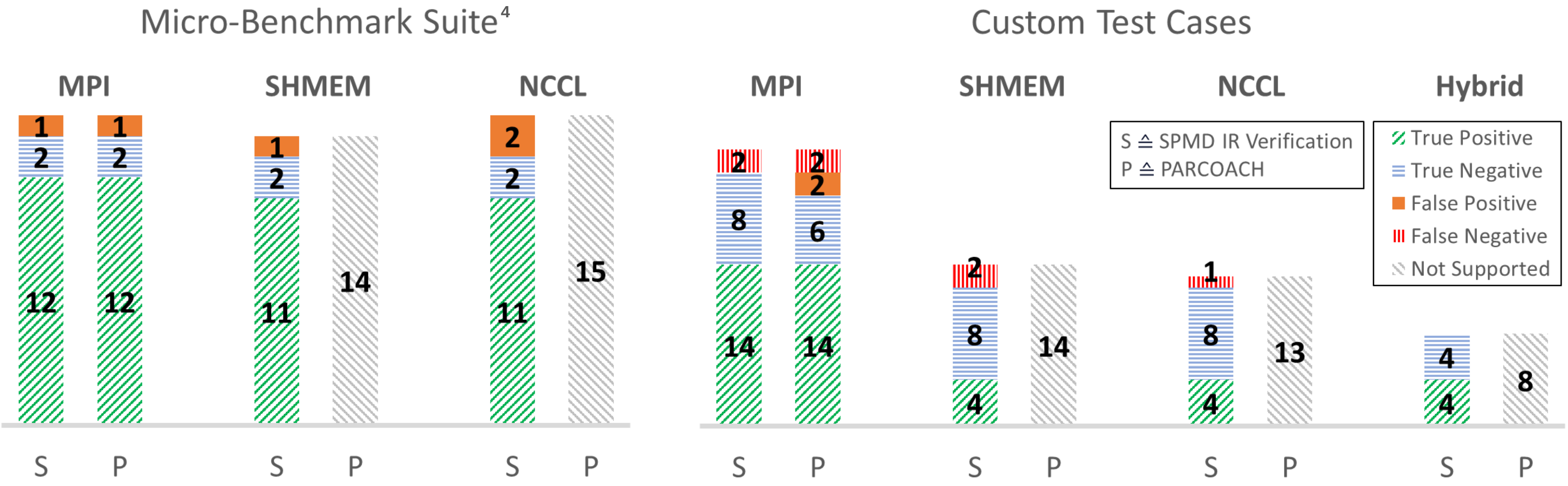
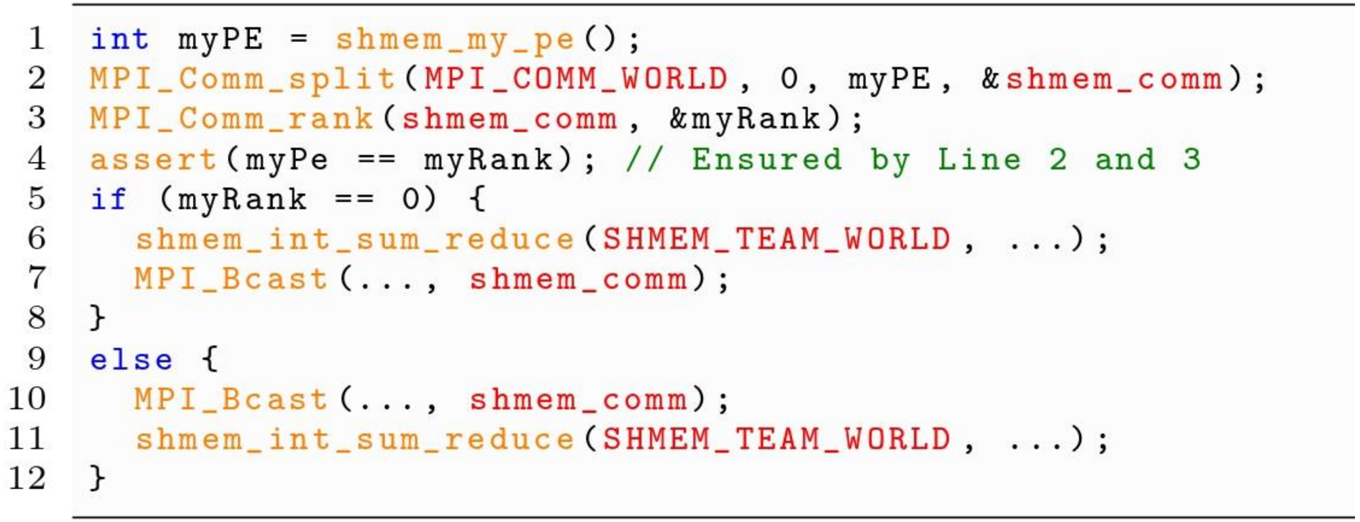


- SPMD IR
  - covers two test cases correctly, where PARCOACH fails
  - has one false positive for one NCCL port
  - besides MPI, also supports SHMEM, NCCL, and their hybrid combinations

Evaluation: Hybrid Example

```
1  int myPE = shmem_my_pe();
2  MPI_Comm_split(MPI_COMM_WORLD, 0, myPE, &shmem_comm);
3  MPI_Comm_rank(shmem_comm, &myRank);
4  assert(myPe == myRank); // Ensured by Line 2 and 3
5
6
7
8
9
10
11
12
```

Evaluation: Hybrid Example



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 5  if (myRank == 0) {
 6    shmem_int_sum_reduce(SHMEM_TEAM_WORLD, ...);
 7    MPI_Bcast(..., shmem_comm);
 8  }
 9  else {
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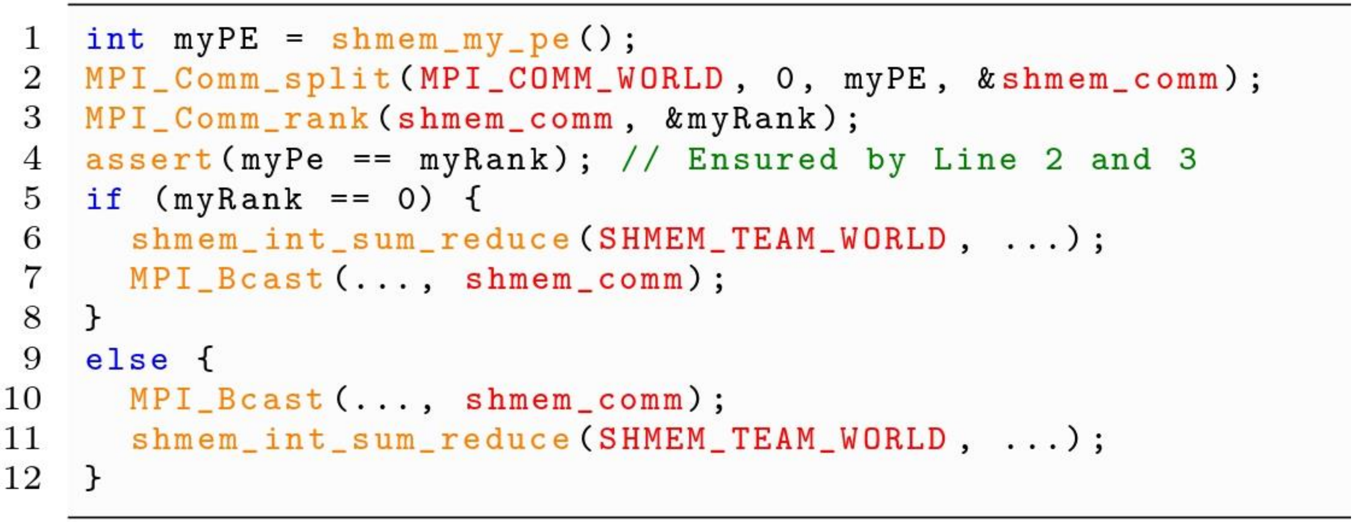

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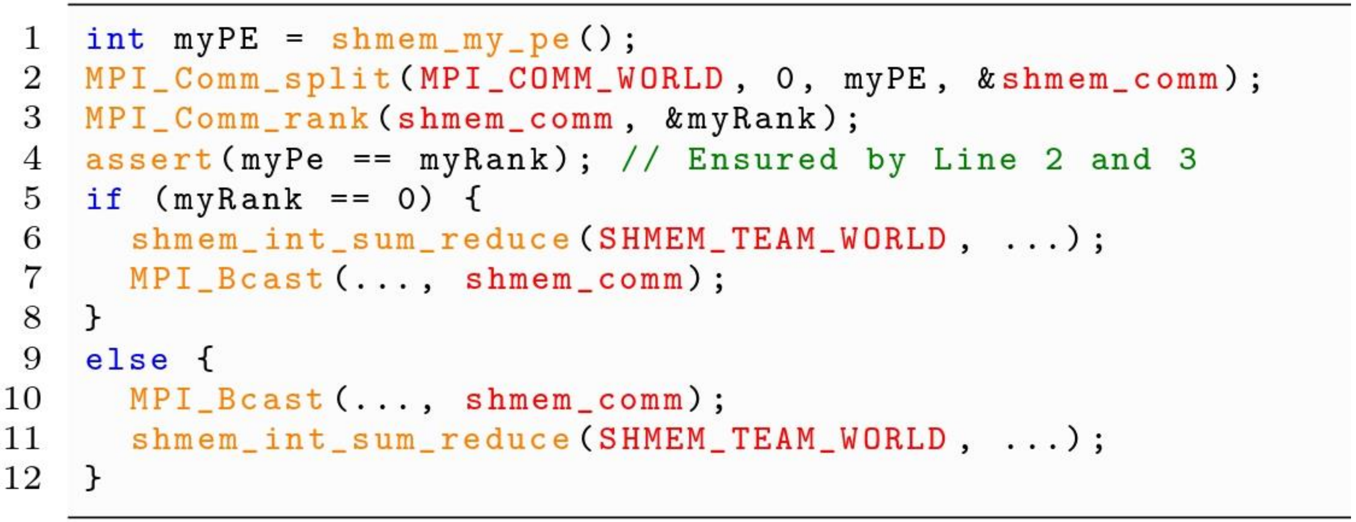

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- The conversion to and representation in the unified SPMD IR addresses this issue

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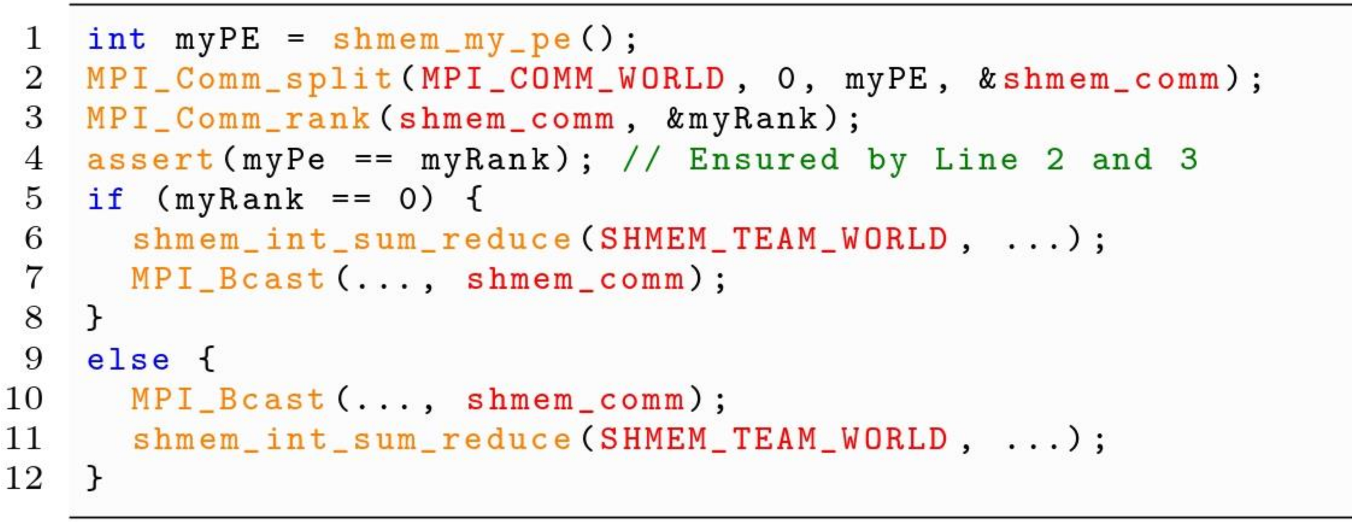

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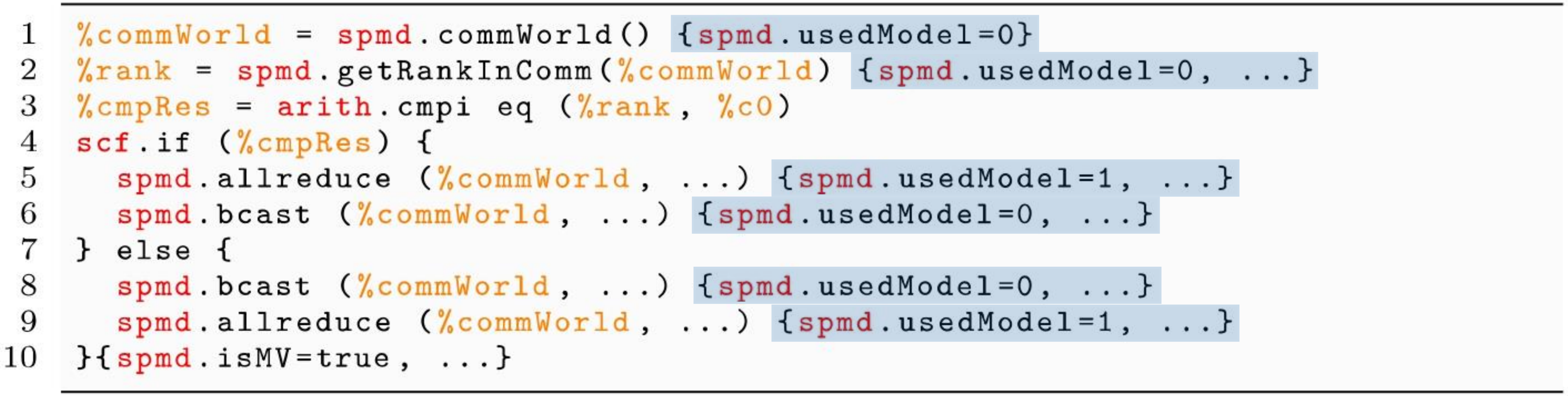

```
%commWorld = spmd.commWorld() {spmd.usedModel=0}
%rank = spmd.getRankInComm(%commWorld) {spmd.usedModel=0, ...}
%cmpRes = arith.cmpi eq (%rank, %c0)
scf.if (%cmpRes) {
  spmd.allreduce (%commWorld, ...) {spmd.usedModel=1, ...}
  spmd.bcast (%commWorld, ...) {spmd.usedModel=0, ...}
} else {
  spmd.bcast (%commWorld, ...) {spmd.usedModel=0, ...}
  spmd.allreduce (%commWorld, ...) {spmd.usedModel=1, ...}
}{spmd.isMV=true, ...}
```

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  - MPI is an extensive standard and programming model

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- So far, executing kind and processes analyses limited to a few patterns for static cases

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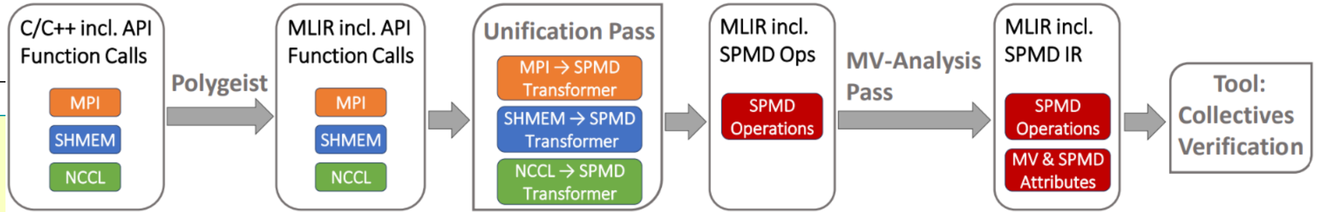
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  - Allowing programming-model-independent analysis and optimization

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Point-To-Point Comm. Non-Blocking Semantics (P2P and Collectives)

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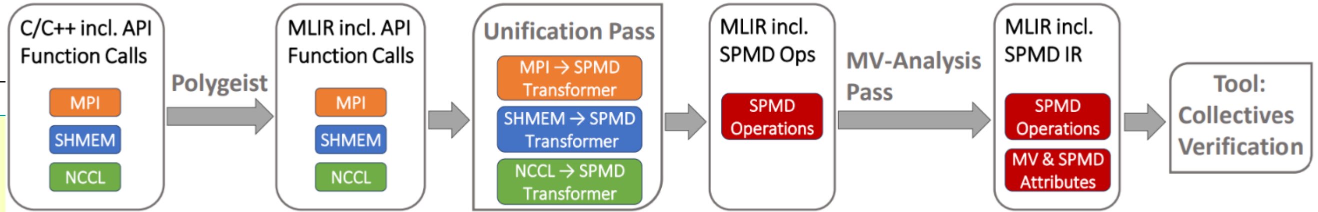
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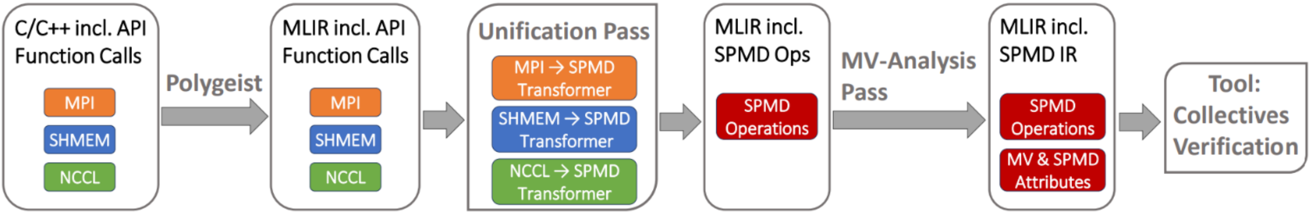

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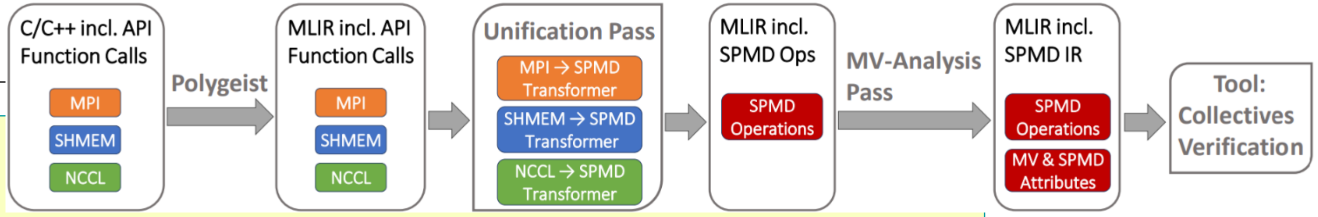

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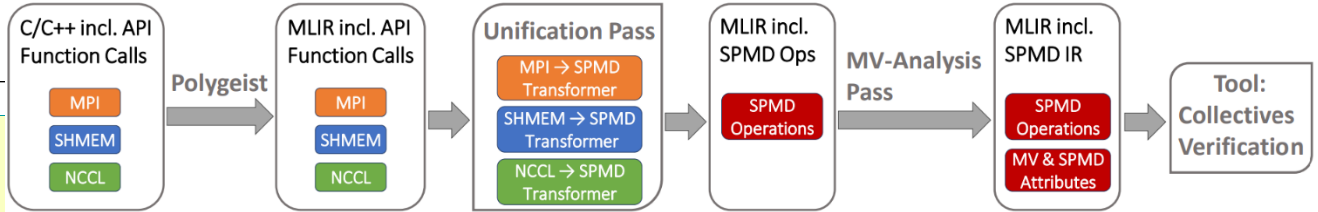

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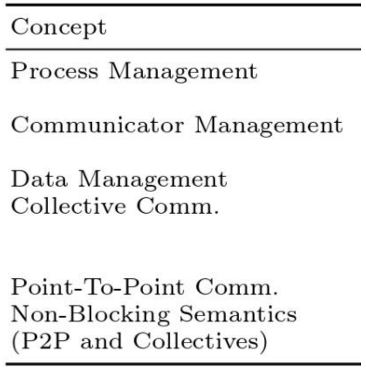
  - First collectives verification for NCCL and SHMEM, and their hybrid combinations with MPI



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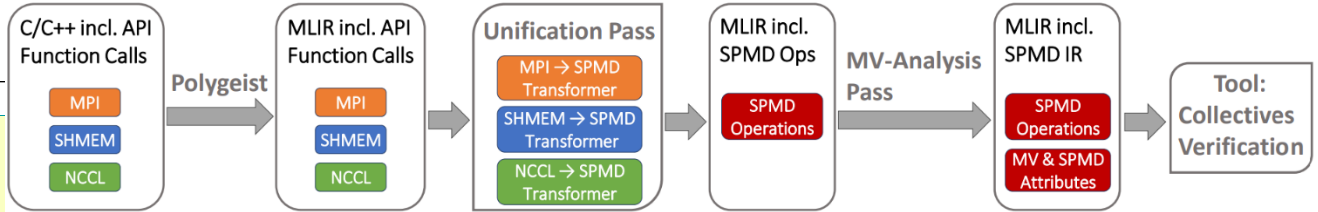
Non-Blocking Semantics (P2P and Collectives)

Conclusion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Summary:

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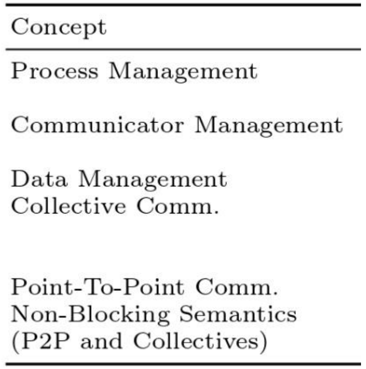

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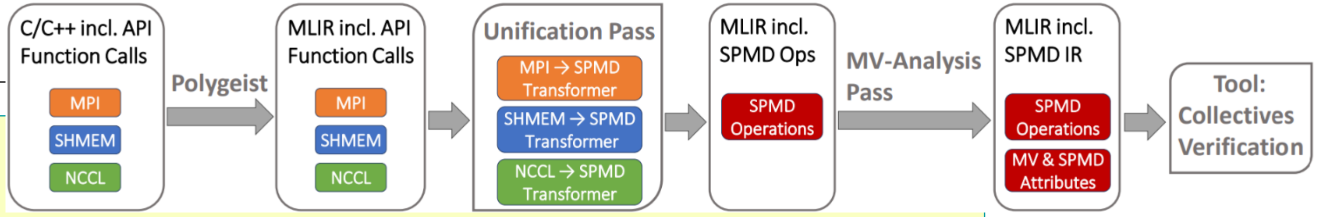

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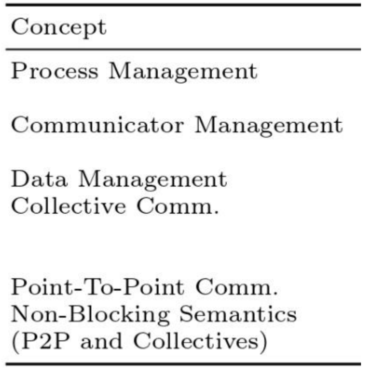

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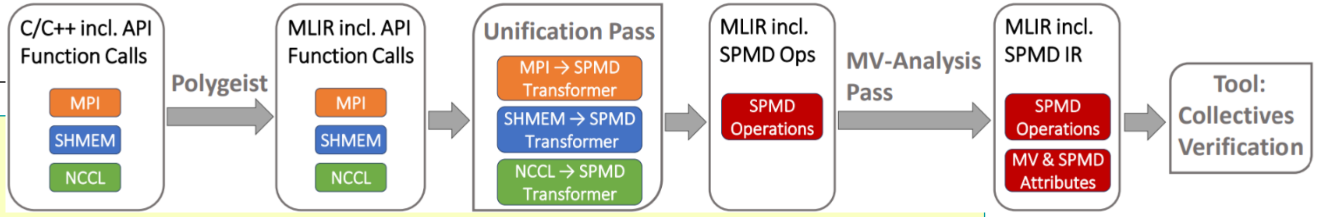

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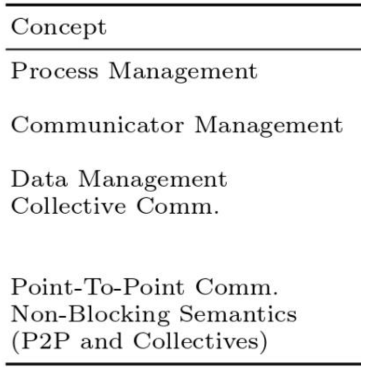

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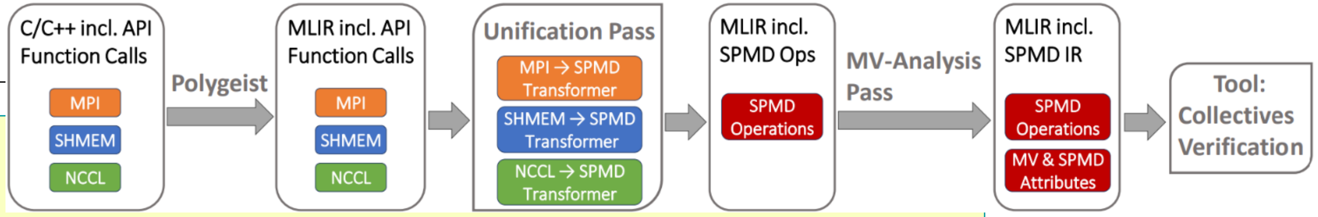
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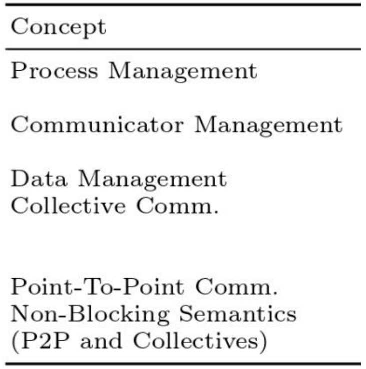

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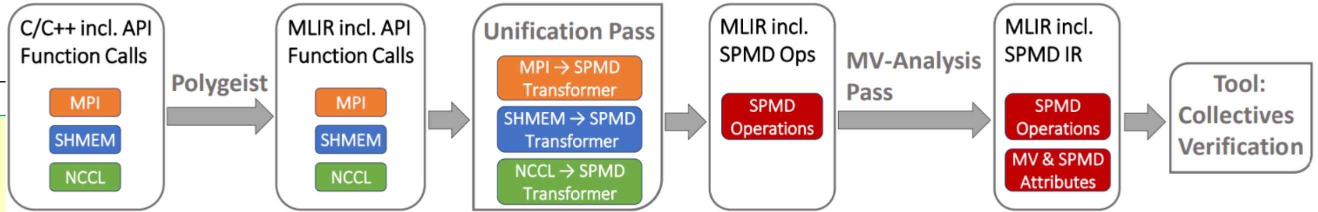

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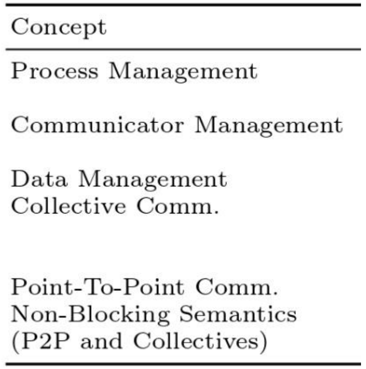

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- Assess approach and workflow on more realistic codes such as proxy apps