# Parallelization in OpenFOAM for HPC Deployment

Mohammed Elwardi Fadeli[1,2], Holger Marschall[1] and Christian Hasse[2]

April, 2023

[1] Mathematical Modeling and Analysis (MMA)
[2] Simulation of Reactive Thermo Fluid Systems (STFS)
Energy Conversion Group, NHR4CES - TU Darmstadt

## Motivation

- Solving some problems requires more computing power than what typical machines provide.
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  - **Machine clusters: MPI** $\leftarrow$ our workshop's scope
  - Custom accelerator hardware (GPUs, FPGAs, ..., etc)

## NHR4CES - Simulation and Data Labs - SDL Energy Conversion

And more **team members here** - working on

Computationally efficient HPC-ready, (reactive)CFD software and methods.

# Parallelization in OpenFOAM for HPC Deployment

## Agenda

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# Lecture section: Agenda

| | Worksop Activities |
|---|---|
| April, 3rd 2023 | Presentation / Questions |
| —————— | ————— |
| April, 13th 2023, 10 AM CET | Hands-on sessions |

Presentation / Questions:

- Go through the lecture videos at your own pace
- Ask about unclear concepts throughout the next 10 days

—————:

- Prepare for hands-on sessions

Hands-on sessions:

- See how it's done
- Apply what you see to parallelize code
- Fight bugs, on your favourite OF fork

## Lecture section: Table of contents

# Parallelization in OpenFOAM for HPC Deployment

## General Introduction

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## The power of parallel workers

**Figure 1:** Parallel work during F1 Pit stops; CC BY 2.0, from commons.wikimedia.org

## Types of Parallelism

**Data Parallelism**
Work units execute the same operations on a (distributed) set of data: **domain decomposition**.

**Task Parallelism**
Work units execute on different control paths, possibly on different data sets: **multi-threading**.

**Pipeline Parallelism**
Work gets split between producer and consumer units that are directly connected. Each unit executes a single phase of a given task and hands over control to the next one.

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## Domain decomposition in OpenFOAM

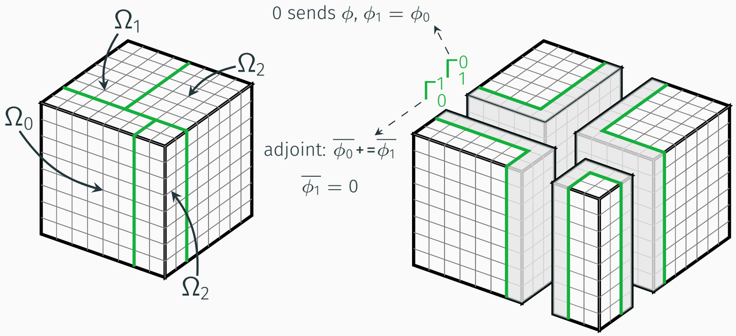
**simple**
: Simple geometric decomposition, in which the domain is split into pieces by direction

**hierarchical**
: Same as simple, but the order in which the directional split is done can be specified

**metis & scotch**
: Require no geometric input from the user and attempts to minimize the number of processor boundaries. Weighting for the decomposition between processors can be specified

**manual**
: Allocation of each cell to a particular processor is specified directly.

# Domain decomposition in OpenFOAM: Processor boundaries



$\Omega_1$
$\Omega_2$
$\Omega_0$
$\Omega_2$
0 sends $\phi$, $\phi_1 = \phi_0$
$\Gamma_1^0$
$\Gamma_0^1$
adjoint: $\overline{\phi_0} \mathrel{+}= \overline{\phi_1}$
$\overline{\phi_1} = 0$

**Figure 2:** Classical halo approach for inter-processor communication

- Use of a layer of ghost cells to handle comms with neighboring processes $\rightarrow$ MPI calls not self-adjoint
- Artificial increase in number of computations per process (and does not scale well)

## Domain decomposition in OpenFOAM: Processor boundaries

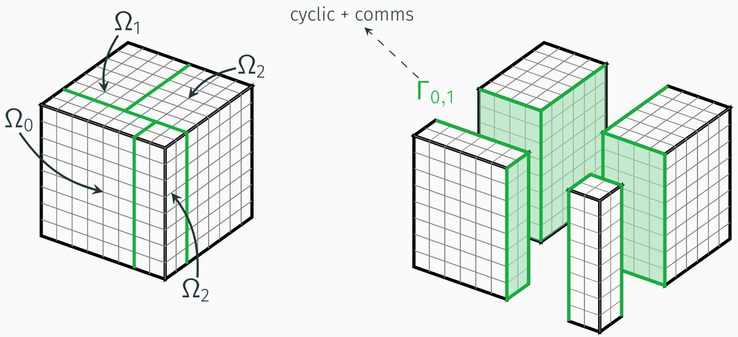


**Figure 3:** Zero-halo approach for inter-processor communication in OpenFOAM

- Communications across process boundaries handled as a BC
- MPI calls are self-adjoint; all processes perform the same work at the boundaries

## Domain decomposition in OpenFOAM: Processor boundaries

**Communicate efficiently through processor boundaries**

```
// Swap boundary face lists through
// processor boundary faces
// This code runs on all processors
syncTools::swapBoundaryFaceList(mesh(), faceField);
// Now faceField has values from the other side
// of the processor boundary
```

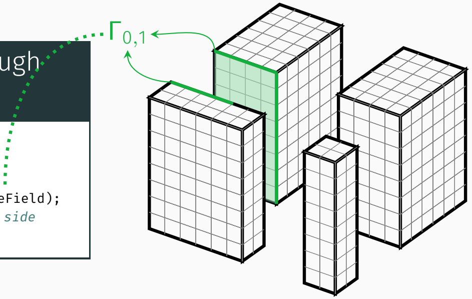


**Figure 4:** Swapping boundary fields across processor boundaries

- Standard API for common processor boundary fields operations
  $\rightarrow$ Generalized for coupled patches, little to no micro management!
- Same local operations carried out on both processors (No checking for processor ranks … etc)

## Modes of Parallelism

**Distributed Memory**

Message Passing Interface (**MPI**): Execute on multiple machines.

**Shared Memory**

Multi-threading capabilities of programming languages, OpenMP:
One machine, many CPU cores.

**Data Streaming**

CUDA and OpenCL. Applications are organized into streams (of same-type elements) and kernels (which act on elements of streams) which is suitable for accelerator hardware (GPUs, FPGAs, ..., etc).

## MPI with OpenFOAM

### Does ’echo’ work work with MPI?

```
mpirun -n 3 echo Hello World!
```

```
Hello World!
Hello World!
Hello World!
```

### What about a solver binary?

```
mpirun -n 3 icoFoam
```

This runs on ”undecomposed” cases!

## MPI with OpenFOAM

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**But the solver is linked to libmpi!**

```
ldd $(which icoFoam)
```

... libmpi.so ...

## MPI with OpenFOAM

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### What about a solver binary?

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```

This runs on "undecomposed" cases!

### But the solver is linked to libmpi!

```
ldd $(which icoFoam)
```

... libmpi.so ...

### Alright we get it now

```
mpirun -n 3 icoFoam -parallel
```

Needs a decomposed case

## MPI with OpenFOAM: Parallel mode

### Anatomy of MPI programs

```
#include <mpi.h>
void main (int argc, char *argv[])
{
  int np, rank, err;
  err = MPI_Init(&argc, &argv) ;
  MPI_Comm_rank(MPI_COMM_WORLD,&rank);
  MPI_Comm_size(MPI_COMM_WORLD,&np);
  // Do parallel communications
  err = MPI_Finalize() ;
}
```

## MPI with OpenFOAM: Parallel mode

### Anatomy of MPI programs

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  // Do parallel communications
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}
```

### How solver programs look

```
#include "fvCFD.H"
void main (int argc, char *argv[])
{
  #include "setRootCase.H"
  // Defines an argList object,
  // which has a ParRunControl member
  // If -parallel is passed in:
  // MPI_Init called in its ctor
  // MPI_Finalize called in its dtor

  // Time is constructed with
  // <case>/processor<procID> paths
}
```

You don’t have to know MPI API to parallelise OpenFOAM code! But you need the concepts.

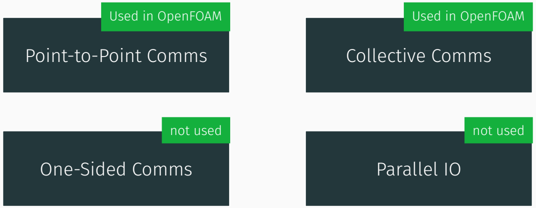
## Objectives

1. Have a basic understanding of Parallel programming with MPI in OpenFOAM Code.
2. Be able to send basic custom object types around using MPI.
3. Be aware of some of the common issues around MPI comms.
4. Acquire enough knowledge to learn more on your own
    - Directly from OpenFOAM's code
    - MPI in general

By the end of the Workshop

→ Be able to parallelize basic serial OpenFOAM code.

## Communication types in MPI



We’ll be focusing on the communications OpenFOAM wraps!

# Parallelization in OpenFOAM for HPC Deployment

## Point-to-Point Communications / General Introduction

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## Communicators and ranks

There may be many processes talking!

**MPI Communicators**

Objects defining which processes can communicate; Processes are referred to by their **ranks**

- `MPI_COMM_FOAM` in the Foundation version and Foam Extend 5
- `MPI_COMM_WORLD` (All processes) elsewhere
- Size: `Pstream::nProcs()`

**MPI rank**

Process Identifier (an integer).

- `Pstream::myProcNo()` returns the active process's ID.

## Serialization and De-serialization: Basics

Premise: resurrect objects from streams of (binary or readable-text) data.

**Standard C++ way**

Manually Override `operator<<` and `operator>>` to interact with stream objects.

- This is used extensively in OpenFOAM
- Newer languages provide automatic serialization at language-level 🧐

**Third-party libs**

Try to handle automatic serialization

- Boost's serialization library if you're into Boost
- `cereal` as header-only library

## Serialization for MPI comms

- MPI defines its own **Data Types** so it can be ”cross-platform”
- OpenFOAM gets around it using **parallel streams** as means of serialization
    - OpenFOAM hands over a stream-representation of your data to MPI calls
    - MPI passes the information in those streams around

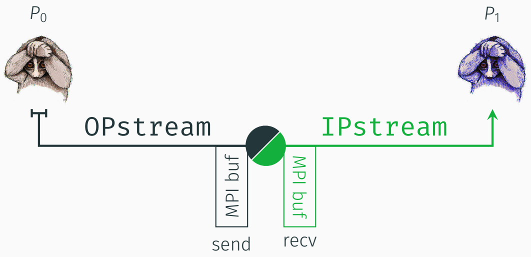

**Figure 5:** Communication between two processes in OpenFOAM

## P2P comms: A first example

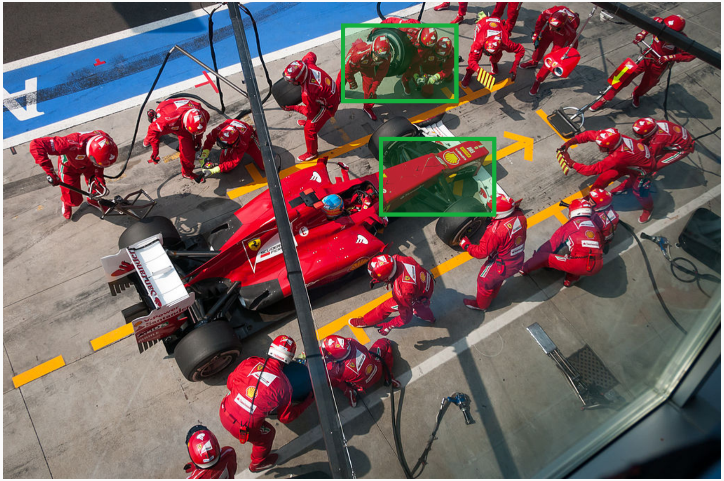

**Figure 1:** Parallel work during F1 Pit stops; CC BY 2.0, from commons.wikimedia.org

## P2P comms: A first example

- `Pstream` class provides the interface needed for communication
- Each ”send” must be matched with a ”receive”

### Slaves talk to master in a P2P fashion

```
if (Pstream::master())
{
    // Receive lst on master
    for
    (
        int slave=Pstream::firstSlave();
        slave<=Pstream::lastSlave();
        slave++
    )
    {
        labelList lst;
        IPstream fromSlave (Pstream::commsTypes::blocking, slave);
        fromSlave >> lst; // Then do something with lst
    }
} else {
    // Send lst to master
    OPstream toMaster (Pstream::commsTypes::blocking, Pstream::masterNo());
    toMaster << localLst;
}
```

# Parallelization in OpenFOAM for HPC Deployment

## Point-to-Point Communications / Blocking comms

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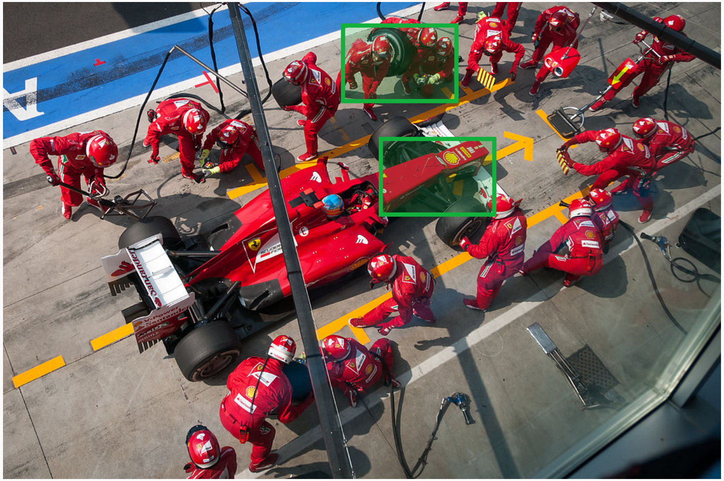

**Figure 1:** Parallel work during F1 Pit stops; CC BY 2.0, from commons.wikimedia.org

## P2P Blocking comms

`Pstream::commsTypes::blocking` (or just `Pstream::blocking` in Foam Extend) defines properties for the MPI call which is executed by the constructed stream.

**Sending** is an asynchronous buffered blocking send

- Block until a copy of the passed buffer is made.
- MPI will send it at a later point, we just can't know when.
- All we know is that the buffer is ready to be used after it returns.

**Receiving** is a blocking receive

- Block until incoming message is copied into passed buffer.

## P2P Blocking comms

`Pstream::commsTypes::scheduled` (or just `Pstream::scheduled` in Foam Extend) lets MPI pick the best course of action (in terms of performance and memory). This may also depend on the MPI implementation.

- Does a ”standard send”, Either:
    1. Do a buffered send (like blocking) if the buffer has enough free space to accommodate sent data.
    2. Fall back to a synchronous send otherwise.
- Both blocking and scheduled comms have a chance of causing deadlocks

**A Deadlock** happens when a process is waiting for a message that never reaches it.

## P2P Blocking comms: Deadlocks

- Either a matching send or a recieve is missing (Definitely a deadlock).
- A send-recieve cycle (Incorrect usage or order of send/recieve calls).

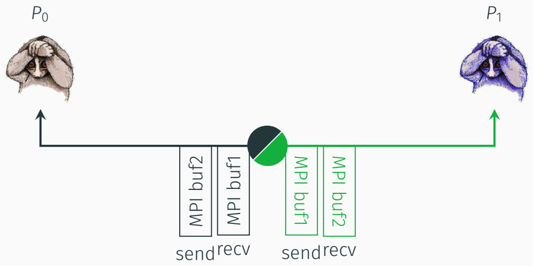

**Figure 6:** Deadlock possibility due to a 2-processes send-recieve cycle (Kind of depends on MPI implementation used!).

## P2P Blocking comms: Stats

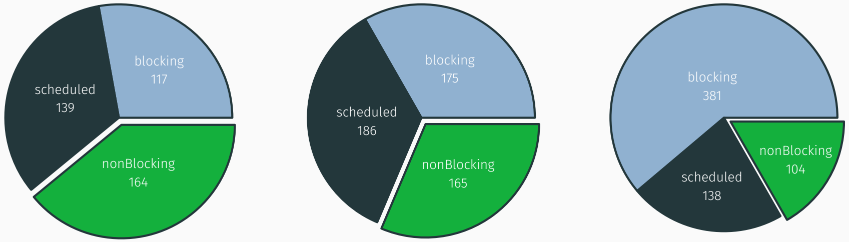

**Figure 7:** Frequency of usage for each type of OpenFOAM comms in OpenFOAM 10 (left), OpenFOAM v2012 (middle) and Foam-Extend 5 (right)

**DISCLAIMER:** Data generated pre-maturely; not suitable to compare forks irt. parallel performance -> Better compare history of the same fork instead.

```
grep -roh -e '::nonBlocking' -e '::blocking' -e '::scheduled' $FOAM_SRC | sort | uniq -c
```

# Parallelization in OpenFOAM for HPC Deployment

## Point-to-Point Communications / Non-Blocking comms

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## P2P Non-Blocking comms

`Pstream::commsTypes::nonBlocking` (or just `Pstream::nonBlocking` in Foam Extend) does not wait until buffers are safe to re-use.

- Returns immediately (similar to ”async” in multi-threading context).
- The program must wait for the operation to complete (`Pstream::waitRequests`).
- It’s a form of piepline parallelism; i.e. Overlaps computation and communication.

- Avoids Deadlocks
- Minimizes idle time for MPI processes
- Helps skip unnecessary synchronisation

## P2P Non-Blocking comms: An example

### Communicate with a neighboring processor

```
// Code for the Foundation version and ESI
PstreamBuffers pBufs(Pstream::commsTypes::nonBlocking);
// Send
forAll(procPatches, patchi)
{
  UOPstream toNeighb(procPatches[patchi].neighbProcNo(), pBufs);
  toNeighb << patchInfo;
}
pBufs.finishedSends(); // <- Calls Pstream::waitRequests
// Receive
forAll(procPatches, patchi)
{
  UIPstream fromNb(procPatches[patchi].neighbProcNo(), pBufs);
  Map<T> nbrPatchInfo(fromNb);
}
```

## Overlapping communication and computation

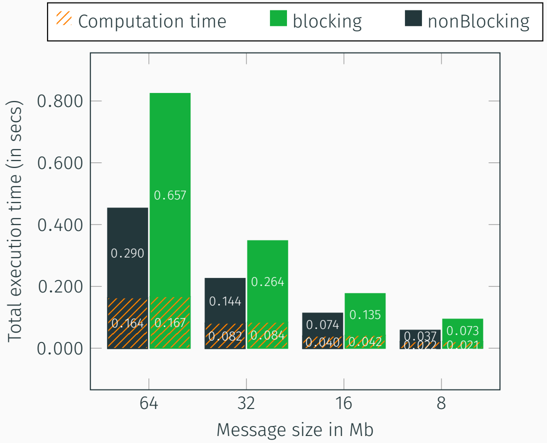
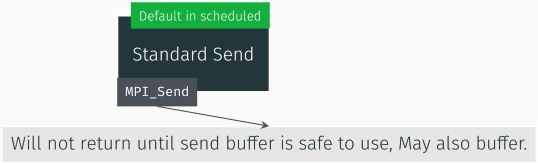


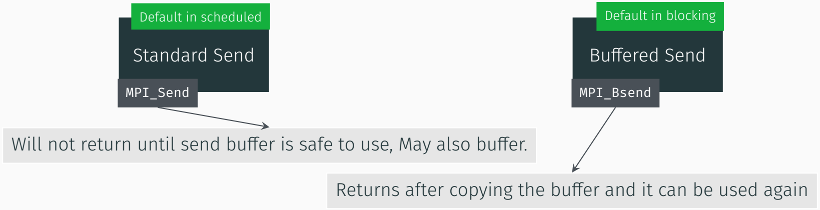
**Figure 8:** Effect of message size on overlapping communication and computation (4 processors, OpenMPI 4, OpenFOAM 8); Benchmark inspired from [2]

# MPI send modes used in OpenFOAM code



Will not return until send buffer is safe to use, May also buffer.

# MPI send modes used in OpenFOAM code



Will not return until send buffer is safe to use, May also buffer.

Returns after copying the buffer and it can be used again

## MPI send modes used in OpenFOAM code

Default in nonBlocking

Non-Blocking standard Send

`MPI_Isend`

Default in scheduled

Standard Send

`MPI_Send`

Will not return until send buffer is safe to use, May also buffer.

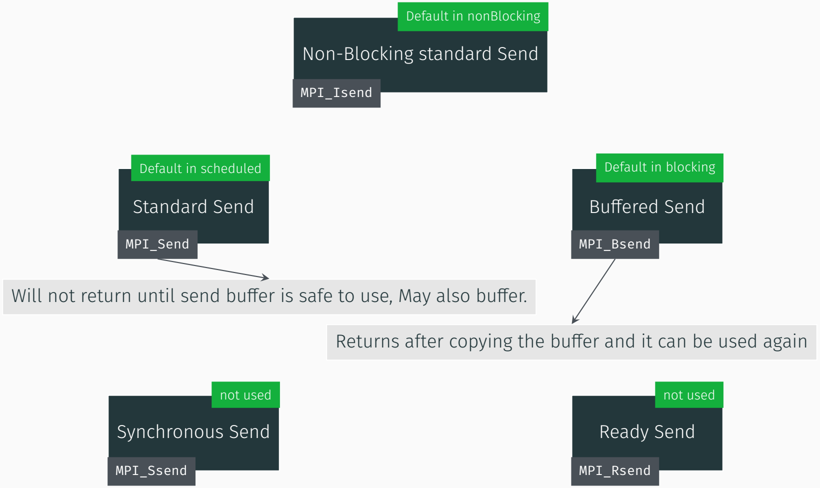
Default in blocking

Buffered Send

`MPI_Bsend`

Returns after copying the buffer and it can be used again

## MPI send modes used in OpenFOAM code



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# Parallelization in OpenFOAM for HPC Deployment

## Collective Communications / General Introduction

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## Collective comms

When Two or more processes talk to each other.

- **All processes** call the same function with the same set of arguments.
- Although MPI-2 has non-blocking collective communications, OpenFOAM uses only the blocking variants.
- NOT a simple wrapper around P2P comms.
- Most collective algorithms are $log(nProcs)$

## Collective comms

- OpenFOAM puts their interface in **static public methods** of `Pstream` class.
    - Major differences in the API across forks: (ESI and Foundation version) vs Foam Extend.
- Gather (all-to-one), Scatter (one-to-all), All-to-All variants of all-to-one ones.
- What OpenFOAM calls a ”reduce” is Gather+Scatter. This significantly differs from MPI’s concept of a reduce which is an all-to-one operation.
- MPI has also a ”Broadcast” and ”Barrier” but these are not used in OpenFOAM.

# Parallelization in OpenFOAM for HPC Deployment

## Collective Communications / Common API

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## Collective comms: Gather (All-to-one)

Check how something is distributed over processors

```
bool v = false;
if (Pstream::master()){ v = something(); } // <- must do on master
Pstream::gather(v, orOp<bool>());  // <- root process gathers
```

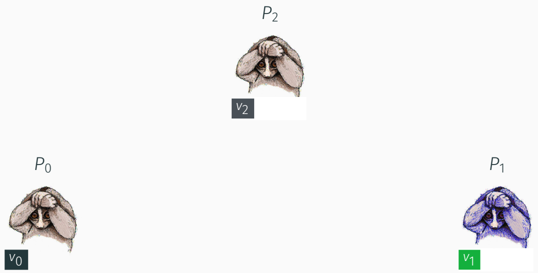

**Figure 9:** An example OpenFOAM gather operation (More like a MPI-reduce)

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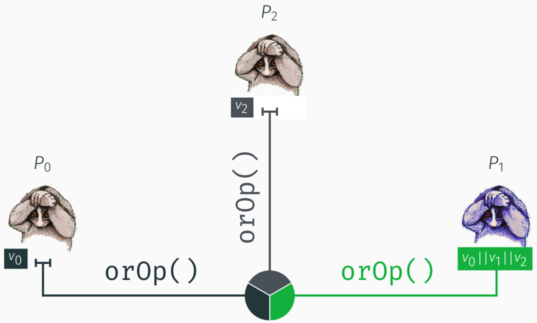

Figure 9: An example OpenFOAM gather operation (More like a MPI-reduce)

## Collective comms: Gather (All-to-one)

Check how something is distributed over processors (List-like)

```
List<bool> localLst(Pstream::nProcs(), false);
localLst[Pstream::myProcNo()] = something();
Pstream::gatherList(localLst); // <- root process gathers
```

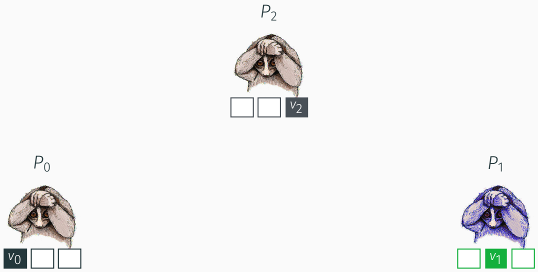

**Figure 10:** Example OpenFOAM gather operation on list items

## Collective comms: Gather (All-to-one)

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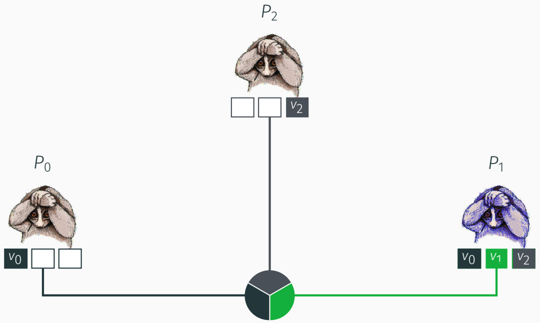

**Figure 10:** Example OpenFOAM gather operation on list items

## Collective comms: Scatter (One-to-all)

### Make processes know about something

```cpp
bool v = false;
if (Pstream::master()){ v = something(); } // <- must do on master
Pstream::scatter(v);  // <- root process scatters
```

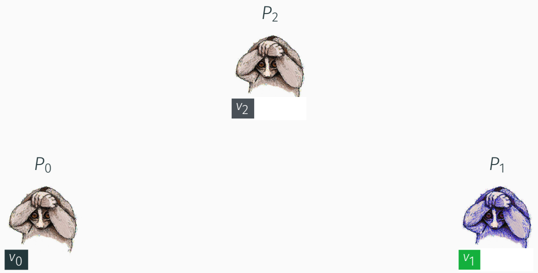

**Figure 11:** An example OpenFOAM scatter operation (More like a MPI-Bcast)

## Collective comms: Scatter (One-to-all)

**Make processes know about something**

```
bool v = false;
if (Pstream::master()){ v = something(); } // <- must do on master
Pstream::scatter(v);  // <- root process scatters
```

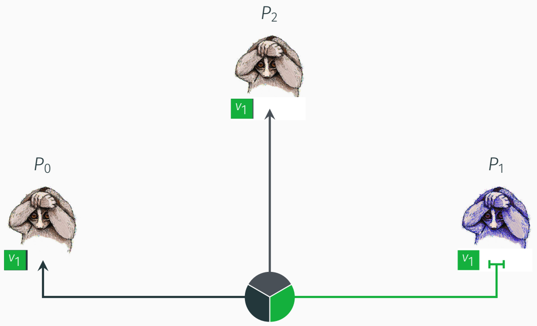

**Figure 11:** An example OpenFOAM scatter operation (More like a MPI-Bcast)

## Collective comms: Scatter (One-to-all)

### Make processes know about something (List-like)

```cpp
List<bool> localLst(Pstream::nProcs(), false);
if (Pstream::master()){ forAll(localLst, ei) { localLst[ei] = something(); } }
Pstream::scatterList(localLst); // <- root process scatters
```

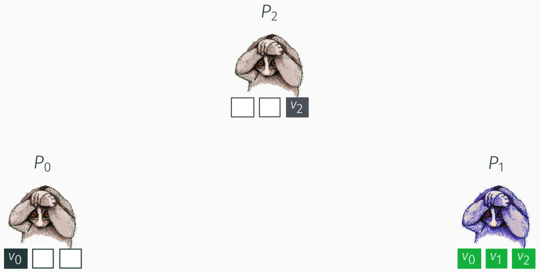

**Figure 12:** Example OpenFOAM scatter operation on list items

## Collective comms: Scatter (One-to-all)

### Make processes know about something (List-like)

```
List<bool> localLst(Pstream::nProcs(), false);
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```

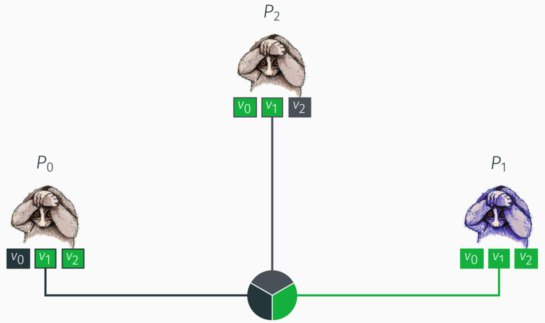

**Figure 12:** Example OpenFOAM scatter operation on list items

## Collective comms: API stats

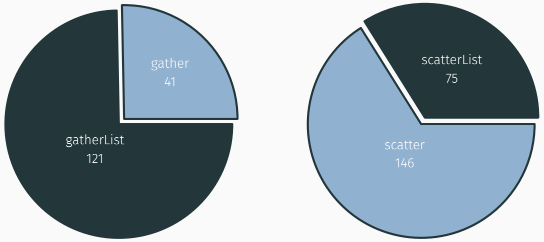

**Figure 13:** Frequency of usage for each API call of OpenFOAM collective comms (v2012)

- There are also some Fork-specific interface methods we won't discuss (eg. `Pstream::exchange`)

## Collective comms: Reduce (All-to-All)

### Do something with a var on all processors (eg. sum them up)

```
// Second arg: a binary operation function (functors); see ops.H
Foam::reduce(localVar, sumOp<decltype(localVar)>());
localVar = Foam::returnReduce(nonVoidCall(), sumOp<decltype(localVar)>());
```

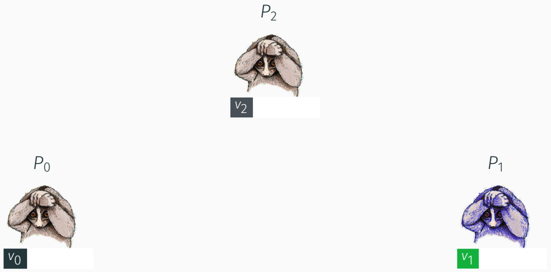

**Figure 14:** An example OpenFOAM reduce operation (MPI-Allreduce)

## Collective comms: Reduce (All-to-All)

**Do something with a var on all processors (eg. sum them up)**

```cpp
// Second arg: a binary operation function (functors); see ops.H
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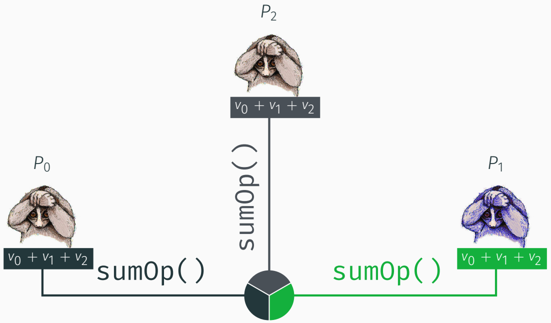

**Figure 14:** An example OpenFOAM reduce operation (MPI-Allreduce)

## Oh, there is a reduce here!

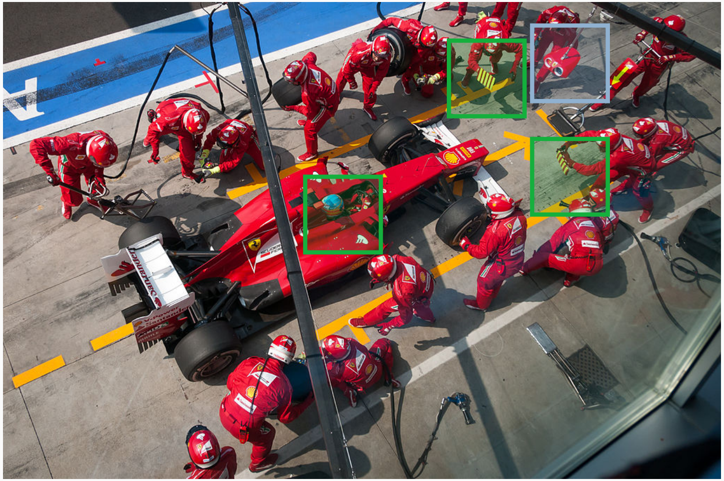

**Figure 1:** Parallel work during F1 Pit stops; CC BY 2.0, from commons.wikimedia.org

## What if one of them just walks away before work is done?

**Figure 1:** Parallel work during F1 Pit stops; CC BY 2.0, from commons.wikimedia.org

## Collective comms: Issues

You can still fall for endless loops if you're not careful!

### Infinite loops due to early returns and collective comms

```cpp
void refineMesh(fvMesh& mesh, const label& globalNCells)
{
  label currentNCells = 0;
  do
  {
    // Perform calculations on all processors
    currentNCells += addCells(mesh);
    // On some condition, a processor should not continue, and
    // returns control to the caller
    if (Pstream::myProcNo() == 1) return; // <-- oops, can't do this
    // !!! who exactly will reduce this! 🤦
    reduce(currentNCells, sumOp<label>());
  } while (currentNCells < globalNCells);
  return;
}
```

# Parallelization in OpenFOAM for HPC Deployment

## How do I send my own data?

Mohammed Elwardi Fadeli[1,2], Holger Marschall[1] and Christian Hasse[2]

April, 2023

[1] Mathematical Modeling and Analysis (MMA)
[2] Simulation of Reactive Thermo Fluid Systems (STFS)
Energy Conversion Group, NHR4CES - TU Darmstadt

# Sending around a simple struct

Say we have something like this:

Push an edge from master to All

```cpp
struct Edge {
    label destination = -1;
    scalar weight = 0.0;
};
// Local edge is always initialized to (-1, 0) on all processors
Edge ej;
// Change it only on master
if (Pstream::master())
{
    ej.destination = 16;
    ej.weight = 5.2;
}
// Try scatter the edge from master to all processes
Pstream::scatter(ej); 😱
```

error: No match for `operator<<(OPstream&,Edge&)`
error: No match for `operator>>(IPstream&,Edge&)`

## Sending around a simple struct

So, Edges can't be communicated as MPI messages, provide the necessary serialization and de-serialization operators:

**Stream Operators for Edge class**

```
// Compiler wants serialization to OPStream/IPStream
// But we better write for the bases OStream/IStream
Ostream&  operator<<(Ostream& os, Edge& e) {
    os << e.destination << " " << e.weight;
    return os;
}
Istream&  operator>>(Istream& is, Edge& e) {
    is >> e.destination;
    is >> e.weight;
    return is;
}
```

```
Info << ej;
```
"16 5.2"

## How about sending a list of custom objects?

### Gathering info about Edges on all procs

```cpp
using Graph = List<List<Edge>>;
// Start with an empty graph on all processes
Graph g(Pstream::nProcs(), List<Edge>());
// Process g[Pstream::myProcNo()] locally on the corresponding proc
Pstream::gatherList(g);
Pstream::scatterList(g);

// Check graph edges on all processes
Pout << g << endl;
```

Compiles, and works as expected if Edge is modified so it can be put in a List

A Better way: Make Edge a child of one of the OpenFOAM classes

### Better ways to define an Edge

```cpp
struct Edge : public Tuple2<label, scalar> {};
// That's it, Edge is now fully MPI-ready
```

## What if the struct has a pointer?

### Easiest solution -> Follow all pointers

```cpp
struct Edge {
    int* destination = nullptr;
    scalar weight = 0.0;
};
Ostream&  operator<<(Ostream& os, Edge& e) {
    os << *e.destination << " " << e.weight;
    return os;
}
Istream&  operator>>(Istream& is, Edge& e) {
    int o; is >> o; e.destination = &o;
    is >> e.weight;
    return is;
}
Edge ej;
if (Pstream::master())
{
    ej.destination = &ej;
    ej.weight = 5.2;
}
```

Hoping that all members are deep-copyable
* Code for illustration only, do not use raw pointers

## What if the struct has a reference to the mesh?

- Unlike pointers, references in C++ need to be initialized when declared (in constructors for members of a reference type).
- You'll most likely have a reference to the mesh → It's good practice.
- The mesh is special because we know that it's partitioned. And we want our objects to use the mesh on the other process when we send them over!

The solution includes:

- Switch to `LinkedList` instead of random-access ones.
  → Why? Because they allow for passing custom constructor arguments.
- The Edge will have to get a new construction function (usually something nested in a sub-class `Edge::iNew::operator()`)
- We will explore this in more detail during the hands-on sessions

# Parallelization in OpenFOAM for HPC Deployment

Application examples & advanced topics

Mohammed Elwardi Fadeli[1,2], Holger Marschall[1] and Christian Hasse[2]

April, 2023

[1] Mathematical Modeling and Analysis (MMA)
[2] Simulation of Reactive Thermo Fluid Systems (STFS)
Energy Conversion Group, NHR4CES - TU Darmstadt

## Solving PDEs over decomposed domains (P2P comms)

General Transport Equation for a physical transport property

$$\partial_t \phi + \nabla \cdot (\phi \mathbf{u}) - \nabla \cdot (\Gamma \nabla \phi) = S_\phi(\phi)$$

Discretized form (Finite Volume notation)

$$[\![\partial_t[\phi]]\!] + [\![\nabla \cdot \left(F[\phi]_{f(F,S,\gamma)}\right)]\!] - [\![\nabla \cdot \left(\Gamma_f \nabla[\phi]\right)]\!] = [\![S_I[\phi]]\!].$$

- Receive neighbour values from neighbouring processor.
- Send face cell values from local domain to neighouring processor
- Interpolate to processor patch faces

## Adaptive Mesh Refinement on polyhedral meshes

1. Refine each processor's part of the mesh, but we need to keep the global cell count under a certain value:

**Reduce nAddCells or nTotalAddCells?**

```cpp
label nAddCells = 0;
label nIters = 0;
label nTotalAddCells = 0;
do
{
    nAddCells = faceConsistentRefinement(refineCell);
    reduce(nAddCells, sumOp<label>());
    ++nIters;
    nTotalAddCells += nAddCells;
} while (nAddCells > 0);
```

## Adaptive Mesh Refinement on polyhedral meshes

2. To decide on whether to refine cells at processor boundaries, we need cell levels from the other side:

### ownLevel holds neiLevel after swapping!

```
// Code extracted from Foam Extend 4.1
labelList ownLevel(nFaces - nInternalFaces);
forAll (ownLevel, i)
{
    const label& own = owner[i + nInternalFaces];
    ownLevel[i] = updateOwner();
}

// Swap boundary face lists (coupled boundary update)
syncTools::swapBoundaryFaceList(mesh_, ownLevel, false);

// Note: now the ownLevel list actually contains the neighbouring level
// (from the other side), use alias (reference) for clarity from now on
const labelList& neiLevel = ownLevel;
```

## Advanced topics

The need for Load Balancing in AMR settings

- AMR operations tend to unbalance cell count distribution accross processors
- Using Blocking comms means more idle process time
    - Non-Blocking are not a solution.
    - Spending some time on rebalancing the mesh is.
- Naturally, load balancing itself involves parallel communication!

## Licensing

Questions?

## Compile and link against MPI implementations

Compiler wrappers are your best friends!

**Grab correct compiler/linker flags**

```
mpic++ --showme:compiler
mpic++ --showme:linker
```

-I/usr/lib/x86_64-linux-gnu/openmpi/include/openmpi ...

-pthread -L/usr/lib/x86_64-linux-gnu/openmpi/lib ...

OpenFOAM environment autmatically figures things out for you:

**Typical Make/options file for the ESI fork**

```
include $(GENERAL_RULES)/mpi-rules
EXE_INC = $(PFLAGS) $(PINC) ...
LIB_LIBS = $(PLIBS) ...
```

## Miscellaneous

- MPI standards: Blocking send can be used with a Non-blocking receive, and vice-versa
- But OpenFOAM wrapping makes it ”non-trivial” to get it to work
- You can still use MPI API directly, eg. if you need one-sided communication.
- Overlapping computation and communication for non-blocking calls is implemented on the MPI side, so, put your computations after the recieve call.

## Sources and further reading i

[1] C. Augustine. *Introduction to Parallel Programming with MPI and OpenMP*. Source of the great 'pit stops' analogy. Oct. 2018. URL: `https://princetonuniversity.github.io/PUbootcamp/sessions/parallel-programming/Intro_PP_bootcamp_2018.pdf`.

[2] Fabio Baruffa. *Improve MPI Performance by Hiding Latency*. July 2020. URL: `https://www.intel.com/content/www/us/en/developer/articles/technical/overlap-computation-communication-hpc-applications.html`.

## Sources and further reading ii

[3] Pavanakumar Mohanamuraly, Jan Christian Huckelheim, and Jens-Dominik Mueller. “Hybrid Parallelisation of an Algorithmically Differentiated Adjoint Solver”. In: *Proceedings of the VII European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS Congress 2016)*. Institute of Structural Analysis and Antiseismic Research School of Civil Engineering National Technical University of Athens (NTUA) Greece, 2016. DOI: 10.7712/100016.1884.10290. URL: https://doi.org/10.7712/100016.1884.10290.

[4] B. Steinbusch. *Introduction to Parallel Programming with MPI and OpenMP*. Mar. 2021. URL: https://www.fz-juelich.de/SharedDocs/Downloads/IAS/JSC/EN/slides/mpi/mpi-openmp-handouts.pdf?__blob=publicationFile.

[5] EuroCC National Competence Center Sweden. *Intermediate MPI*. May 2022. URL: https://enccs.github.io/intermediate-mpi/.