



Durham  
University

# A brief introduction to parallel programming on a supercomputer

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<https://www.dur.ac.uk/arc/>

# Course Outline

Basics of parallel programming with OpenMP and MPI using Durham University's supercomputer, Hamilton.

Aims of the course:

- Introduction to parallel programming and to both shared- and distributed-memory model
- Learn how to use MPI commands to pass messages
- Learn about collective and combined parallel communications
- Be familiarised with data handling and higher functions of MPI
- Learn how to make a serial C code multi-threaded by adding pragma directives
- Learn about synchronisation, critical region and atomic directive



# Course Schedule

- 09:00-09:15 – Brief introduction to HPC and parallel programming models
- 09:15-09:30 – Practical 0: “Hello world” with MPI and OpenMP on Hamilton
- 09:30-10:00 – **1. Basics of MPI: Point-to-point communications**
  - 10:00-10:15 – Practical 1: “Ping pong!”
- 10:15-10:45 – **2. Basics of MPI: Collective communications**
  - 10:45-11:00 – Practical 2: “Collective communication”
- 11:00-11:15 - “coffee break”

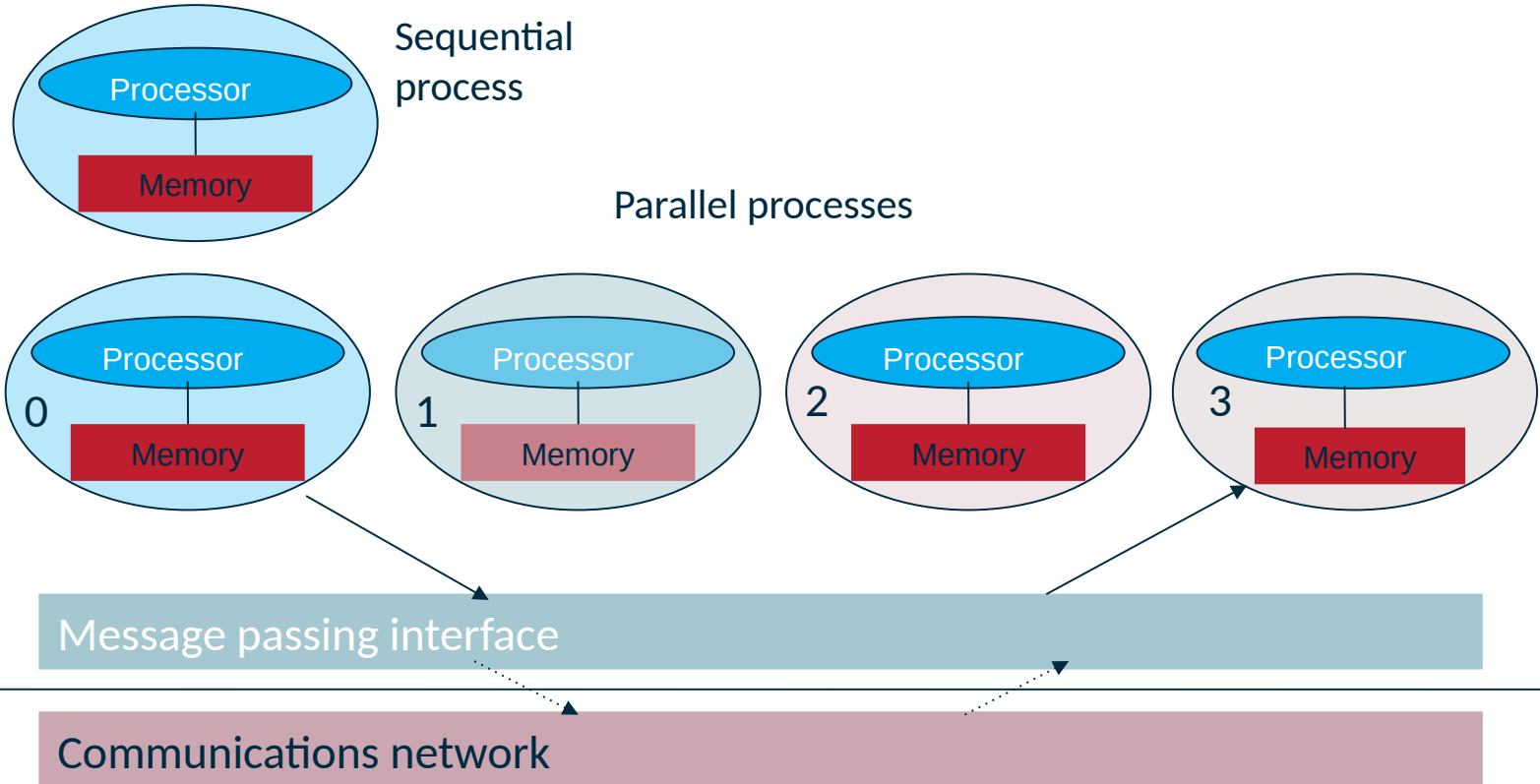


COFFEE BREAK
- 11:15-11:45 – **3. Basics of OpenMP: Parallel worksharing**
  - 11:45-12:00 – Practical 3: OpenMP
- 12:00-12:30 – **4. Basics of OpenMP: Task-based parallelism**
  - 12:30-12:45 – Practical 4: OpenMP
- 12:45-13:00 – Conclusion



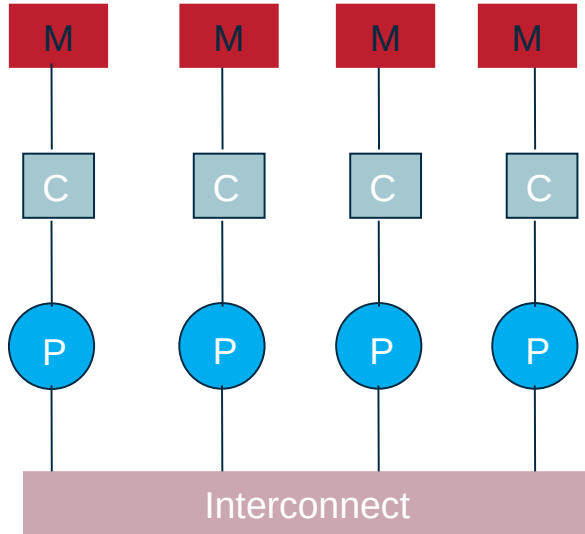
# 1. Brief intro to HPC and parallel programming models

## 1.1 Message-Passing Paradigm

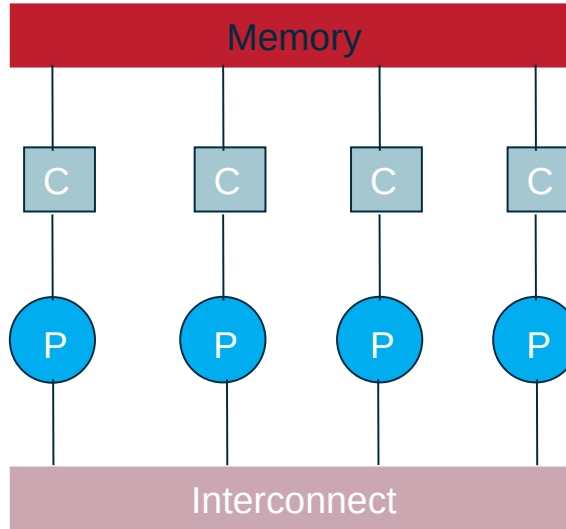


# 1. Brief intro to HPC and parallel programming models

## 1.2 Distributed memory and shared memory systems



Distributed memory system e.g. Beowulf cluster. Architecture matches message passing paradigm.

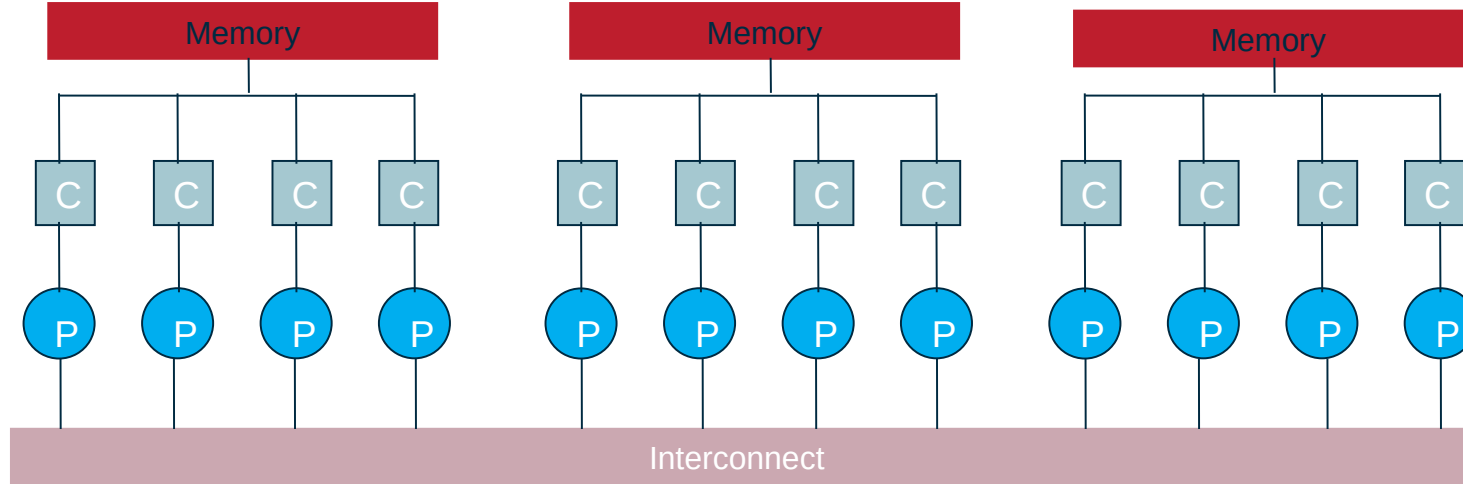


Shared-memory system.  
e.g. multiprocessor desktop PCs.  
Can use interconnect + memory as a communications network  
(the basis of mixed-mode parallelism)



# 1. Brief intro to HPC and parallel programming models

## 1.3 Shared memory clusters

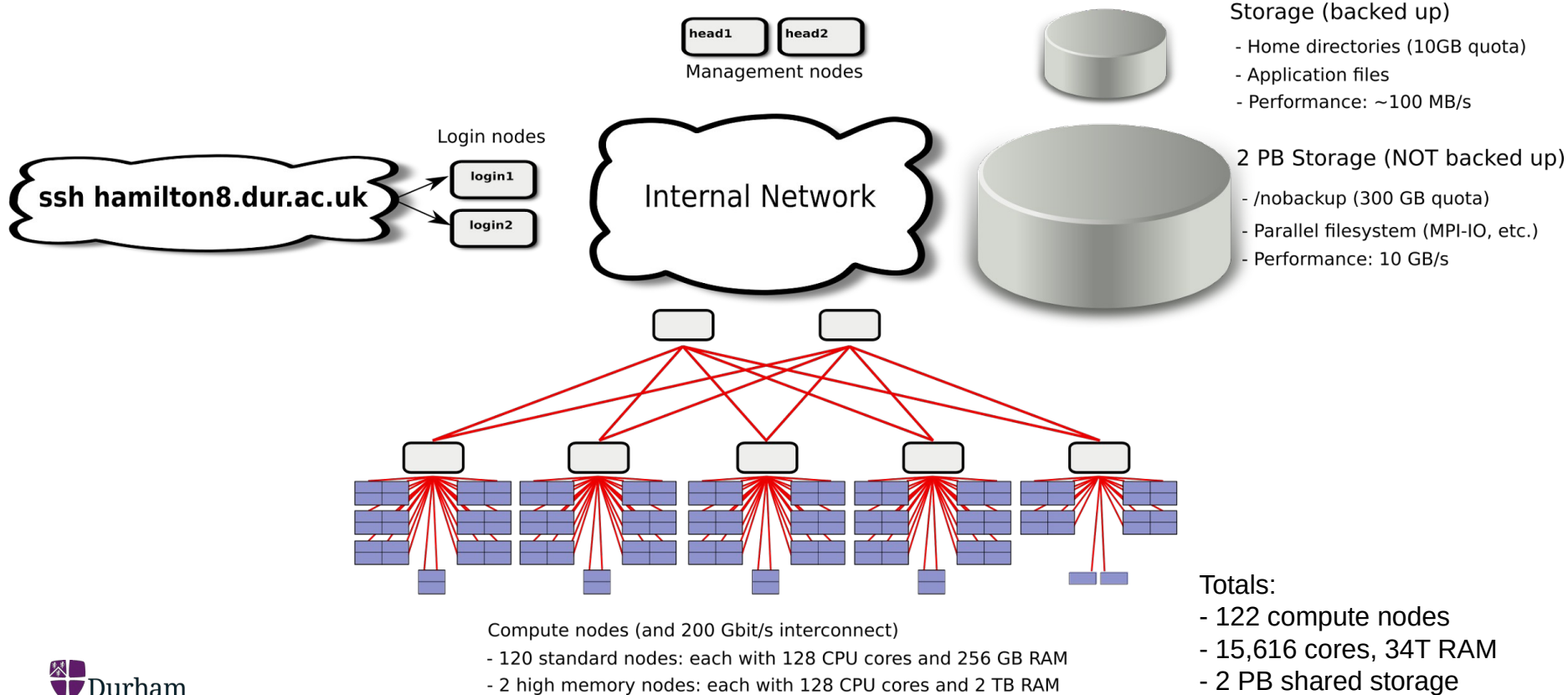


Will use both memory/interconnect to communicate between processes.  
Commonly now found shared memory clusters (e.g., Hamilton!)



# 1. Brief intro to HPC and parallel programming models

## 1.4 Machine architecture: Hamilton



# 1. Brief intro to HPC and parallel programming models

## 1.5 HPC terminology

- Nodes, sockets, cores, threads, processes per core
  - You can run multiple processes and threads per core
  - **MPI** (Message Passing Interface) and **OpenMP** (Open Multi-Processing) are two popular interfaces to describe parallelism. Such interfaces are commonly implemented in standard high-level language such as FORTRAN/C/C++
  - **OpenMP** provides shared-memory model and describes thread parallelism within a process (with common address space). It is realised using compiler directives to facilitate the parallelism
  - **MPI** provides distributed-memory model and describes parallelism between processes (with separate address spaces). It is implemented with calls to a parallel library





# 1. Brief intro to HPC and parallel programming models

## 1.5 HPC terminology (cont.)

- To characterise performance of computing, processor speed is measured in floating point operations per second (*FLOPS*, *MFLOPS*, *GFLOPS*, etc.)
  - There are two speeds: ‘*peak*’ – the best in theory; and ‘*sustained*’ - on a benchmark or relevant user code. The latter can be anything between ~0% and ~80% of ‘peak’ speed
  - For example, a compute node on Hamilton8 has a theoretical *peak speed*: 4096 GFLOPS. HPL benchmark shows 77% efficiency
- To characterize performance of data transfer, intranode (between RAM and core) or internode (between nodes):
  - Bandwidth is the rate at which data can be transferred (*the higher the better*), from KB/s to GB/s
  - Latency is the start-up time for data transfer (*the lower the better*), from ns for L1 cache (a few clock cycles) to ms for Ethernet networks



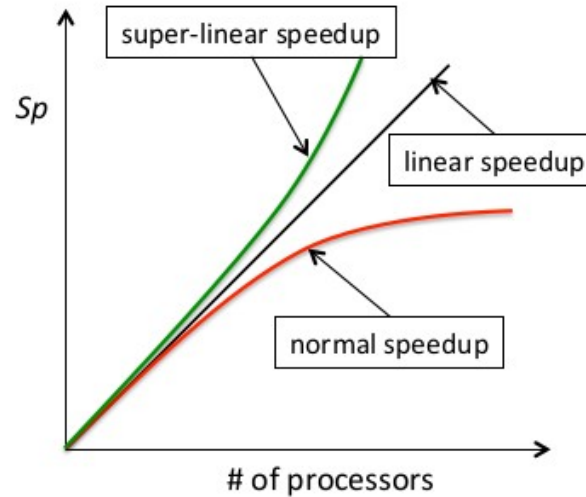
# 1. Brief intro to HPC and parallel programming models

## 1.5 HPC terminology (cont.)

- Speedup:
  - $p = \#$  processes
  - $T_s$  = execution time of the parallel algorithm on a single algorithm on a single process
  - $T_p$  = execution time of the parallel algorithm on  $p$  processes
  - **Amdahl's law** expresses that the potential speed is limited by the sequential part of the program

$$S_p = \frac{T_s}{T_p}$$

- Parallel efficiency:  $E_p = \frac{S_p}{p} = \frac{T_s}{pT_p}$
- Scalability:
  - **Strong scaling** (problem size is fixed), ideally time taken **reduces in direct proportion to number of processes used**
  - **Weak scaling** (problem size scales with # processes), ideally time taken is **constant** and problem **scales directly with number of processes used**
  - usually limited by communications, latency, idling / **load balancing** (static, dynamic)
  - Good load-balancing and efficient communication can clearly all be ruined by **poor process placement!**



# 2 Basics of MPI

## The General Message Passing Paradigm

- All variables are private to each process. Values of variables are held in local memory – a distributed memory parallel computer
- Processes communicate via special subroutine calls to an external library
- Typically:
  - Communications are written in a conventional sequential language
  - A single program is compiled and executed across each processor
  - There is a generic interface i.e. the method/route of communication is hidden.



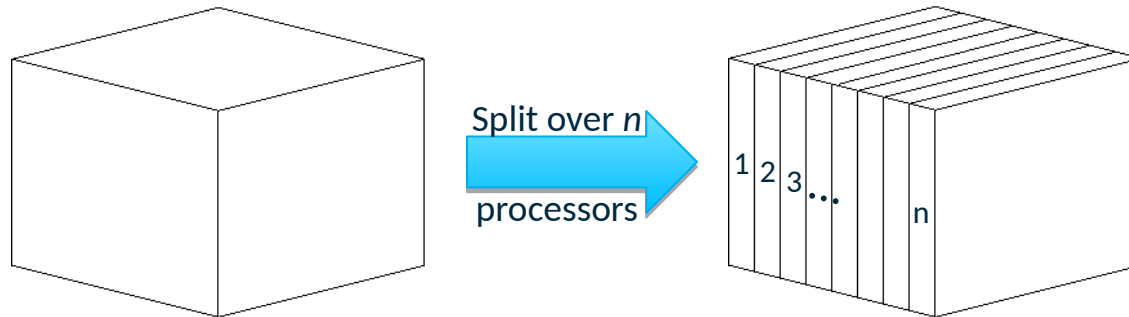
## 2 Basics of MPI

- “The goal of the Message Passing Interface, simply stated, is to develop a widely used standard for writing message-passing programs. As such, the interface should establish a practical, portable, efficient, and flexible standard for message passing.”
  - MPI-1, MPI-2, MPI-3, MPI-4 (1139pp, approved by the MPI Forum June 2021)
- There are multiple implementations (“flavours”) of this standard specification
  - MPICH
  - Open MPI (not the same as OpenMP!)
  - MVAPICH
  - Vendor-specific implementations – Intel® MPI, Cray MPI...



## 2 Basics of MPI

- Aim: to reduce time taken to achieve strong scaling
- Objective: decompose a task into smaller tasks which can be performed simultaneously i.e. in parallel
- Approach 1: domain or data decomposition:



- Approach 2: functional decomposition:
  - e.g. integration: splitting the interval  $\int_a^b f(x)$  over  $n$  processors, e.g.  $(b-a)/n$
  - e.g. Fourier transforms (1D to 3D), passing out pages from a book to each proces, sections of a database



# 2 Basics of MPI

## 2.1 Writing your first MPI program

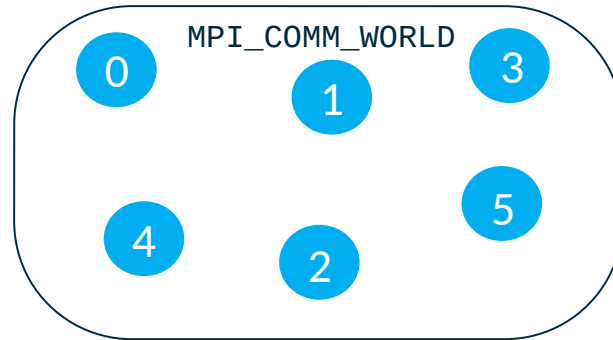
<i>The Standard...</i>	C	FORTRAN
Essential header files	<code>#include &lt;mpi.h&gt;</code>	<code>include 'mpif.h'</code>
Initialisation ( <b>always</b> the first MPI procedure called. Never called more than once)	<pre>int main (int argc, char *argv[]){     MPI_Init(&amp;argc, &amp;argv);</pre>	<pre>INTEGER IERR CALL MPI_INIT(IERR)</pre>
Finalisation ( <b>Essential</b> . Must be the last MPI procedure called)	<pre>MPI_Finalize();</pre>	<pre>CALL MPI_FINALIZE(IERR)</pre>
Function syntax...	<p>Case sensitive...</p> <pre>Error = MPI_Xxxx(parameter, ...); MPI_Xxxx(parameter)</pre>	<p>Case insensitive...</p> <pre>CALL MPI_XXXX(parameter, ..., IERR)</pre> <p>IERR returns 0 (success) or 1 (fail), same as return() in C.</p>



# 2 Basics of MPI

## 2.1 Writing your first MPI program (cont.)

- Communicators define a group of processes between which message passing can occur.
- By default, the communicator `MPI_COMM_WORLD` is automatically generated at initialization, does not need to be declared and contains all processes when execution begins:

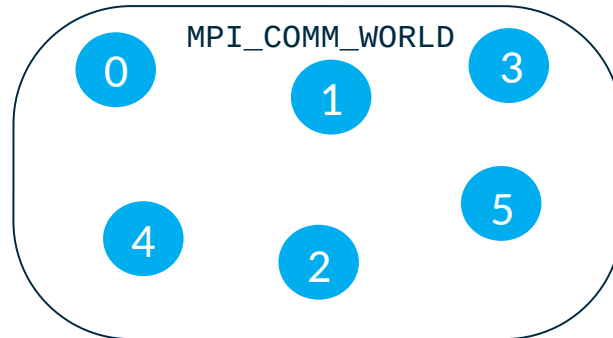


# 2 Basics of MPI

## 2.1 Writing your first MPI program (cont.)

The MPI *rank* returns an integer number for each 'process' in a 'communicator' group, numbered from 0 in both C and FORTRAN. The rank is only defined by MPI and is not linked to any other identified e.g. CPU #, core #, node #

C	FORTRAN
<pre>int rank; MPI_Comm_rank(MPI_COMM_WORLD , &amp;rank);</pre>	<pre>INTEGER RANK, IERR CALL MPI_COMM_RANK(MPI_COMM_WORLD, RANK, IERR)</pre>



The communicator  
MPI\_COMM\_WORLD  
(queried by the commands)  
contains ranks 0 to 5



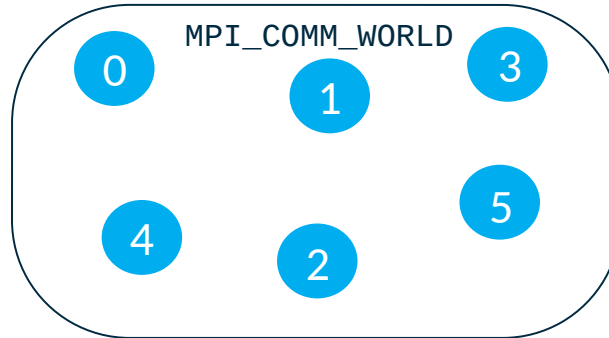


# 2 Basics of MPI

## 2.1 Writing your first MPI program (cont.)

The MPI size returns the total number of ranks in a communicator group, again an integer.

C	FORTRAN
<pre>int size; MPI_Comm_size(MPI_COMM_WORLD , &amp;size);</pre>	<pre>INTEGER SIZE, IERR CALL MPI_COMM_SIZE(MPI_COMM_WORLD, SIZE, IERR)</pre>



The communicator  
MPI\_COMM\_WORLD  
(queried by the commands)  
contains 6 ranks in total



# 2 Basics of MPI

## 2.1 Writing your first MPI program (cont.)

A code checklist...

- Headers: `mpi.h` / `mpif.h`
- Initialisation before anything else MPI: `MPI_Init`
- Rank, size commands: `MPI_Comm_rank` / `MPI_Comm_size`
  - Insert some code employing MPI functionality here!
- Finalisation should be the last MPI procedure: `MPI_Finalize`

With only the header, initialization and finalization, any MPI code will compile and run equivalently to a serial code.



## 2 Basics of MPI

### 2.1 Writing your first MPI program (cont.)

Compilation on Hamilton, after you have logged into your account...

- Hamilton has a module system and by default, no modules are available.
- To see what is available: `module avail`
- To load compilers and MPI:

```
module load intel/2021.4  
module load intelmpi/2021.6
```

- To compile:

C	FORTRAN
<code>mpicc my_prog.c -o myprogram</code>	<code>mpif90 my_prog.f -o myprogram</code>

- To very briefly test on the login node using 4 processes:

```
mpirun -np 4 ./program
```

**But do not make a habit of doing this! Use the queues...**



# 2 Basics of MPI

## 2.1 Writing your first MPI program (cont.)

To fairly share the available resources, Hamilton has a queueing system.

Job.sh file contents:

- To access this, you must write and submit a job script:
- Submit: `sbatch job.sh`
- Status: `squeue -u user`
- Estimated start time:  
`squeue -start -u user`
- Cancel: `scancel jobID`
- Cancel all your jobs:  
`scancel -u user`
- Get account info:  
`sacct -u user`
- Get job info (e.g. total memory used etc.): `sacct -j jobID`

```
#!/bin/bash
#SBATCH --job-name="my-first-script"
#SBATCH -o myscript.%A.out
#SBATCH -e myscript.%A.err
#SBATCH -p test.q
#SBATCH -t 00:05:00
#SBATCH -N 1 # number of nodes
#SBATCH -n 4 # number of tasks (MPI ranks)
#SBATCH -c 4 # number of cores per task

module purge
module load intel/2021.4
module load intelmpi/2021.6
mpirun ./myprogram
```



# Practical 0: Hello World!

- Write a minimal MPI program that prints “Hello World!”
  - Serial template code is available for C and FORTRAN on Hamilton here:-  
`exercises/practical0/helloworld.c`  
`exercises/practical0/helloworld.f90`
- Compile your code.
- Run it on a single processor on the login node.
- Run it on a single processor *via the batch queue*. Job script:  
`exercises/practical0/job.sh`
- Run it on several processors in parallel *via the batch queue*.
- Modify the code (with an if statement) such that only rank 0 prints “Hello World!”
- Modify the code such that the ranks print:-  
“Hello World! I am rank # of size #.”



# Practical 0: Review

C	FORTTRAN
<pre>#include &lt;stdio.h&gt; #include &lt;mpi.h&gt;  int main (int argc, char *argv[]) {     int rank, size;      MPI_Init(&amp;argc, &amp;argv); /* Initialise MPI */     MPI_Comm_rank(MPI_COMM_WORLD, &amp;rank); /* Get rank */     MPI_Comm_size(MPI_COMM_WORLD, &amp;size); /* Get size */      printf("Hello from rank %d of size %d.\n", rank, size);      MPI_Finalize(); }</pre>	<pre>PROGRAM helloworld IMPLICIT none include 'mpif.h' INTEGER rank, size, ierr ! Initialise MPI CALL MPI_Init(ierr) ! get processor rank CALL MPI_Comm_rank(MPI_COMM_WORLD, rank,ierr) ! Get total number of processors CALL MPI_Comm_size(MPI_COMM_WORLD, size,ierr)  write (*,*) 'Hello from rank ',rank,' of size ',size  call MPI_FINALIZE(ierr) end program helloworld</pre>



# 2 Basics of MPI

## 2.2 Point-to-point communications

### Messages

- Data types

### Communication modes and completion

- Sends: synchronous / buffered / ready / standard
- Receive
- Success criteria
- Wildcarding

### Communication envelope

### Message order preservation

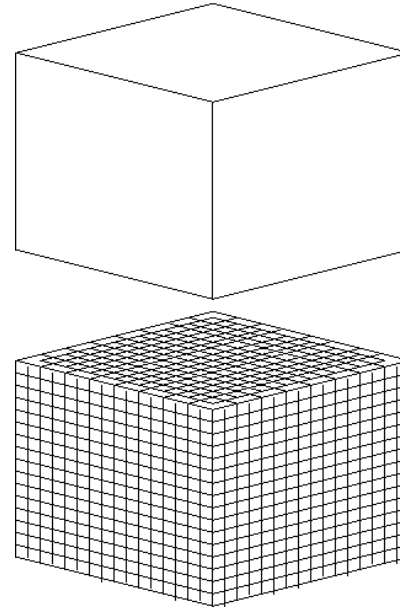
### Combined send and receive



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

- An example: this is a representation of a domain for a piece of CFD software that solves the equations of fluid dynamics to evolve a fluid with time:-
- The domain is broken down into a number of cells:- (e.g.  $20 \times 20 \times 20$ : 8000 cells)
- If solving Euler's equation takes 1 second to evolve the fluid in a cell by one second of simulation time, a single processor would take 8000s to update this whole grid by 1s of simulation time. Evolving the grid by days would correspondingly take 8000x longer – *decades!*
- In some cases, each task is self-contained – cells need only know about their own conditions to calculate their update – and the simulation becomes “embarrassingly parallel”.






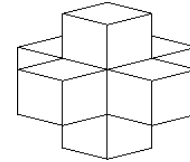
# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

In reality, and certainly in this CFD example, this is not the case.

In our code, each cell: 

In order to calculate the flow between cells and update its own fluid conditions, the code needs to know about the conditions in its neighbours in every direction:



What happens if a neighbouring cell is held in different memory on another process?

- Communication must occur between processes
- “Message passing” is the context in which this takes place, using a message passing interface, or **MPI** library
- The message passing system needs to be aware of the following information:
  - 1) The ‘rank’ of the message source
  - 2) Source buffer: variable / array location
  - 3) MPI data type
  - 4) The ‘rank’ of message destination
  - 5) Destination buffer
  - 6) Size of sending and receiving buffer(s)
- Messages contain a number of elements of a particular data type.



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

C: MPI Data types	FORTTRAN: MPI Data types
MPI_CHAR	MPI_CHARACTER
MPI_SHORT	
MPI_INT	MPI_INTEGER
MPI_LONG	
MPI_UNSIGNED_CHAR	MPI_LOGICAL
MPI_UNSIGNED_SHORT	MPI_COMPLEX
MPI_UNSIGNED	
MPI_UNSIGNED_LONG	
MPI_FLOAT	MPI_REAL
MPI_DOUBLE	MPI_DOUBLE_PRECISION
MPI_LONG_DOUBLE	MPI_REAL8
MPI_BYTE	MPI_BYTE



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

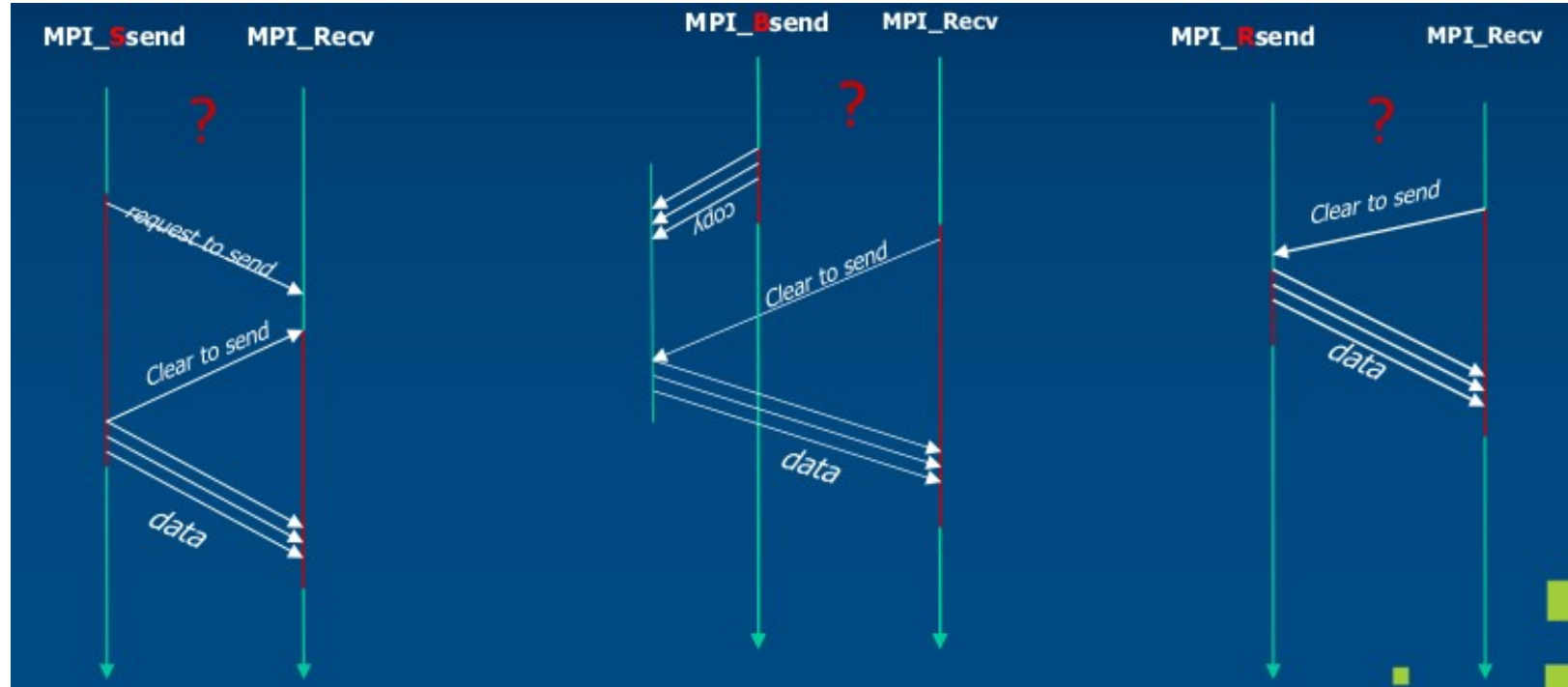
Sender mode	MPI Call	Completion status
Synchronous send	MPI_Ssend	Only completes when the receive has completed.
Buffered send	MPI_Bsend	Always completes (unless an error occurs), irrespective of receiver.
<b>Standard send</b>	<b>MPI_Send</b>	<b>Can be synchronous or buffered (often implementation dependent).</b>
Ready send	MPI_Rsend	Always completes (unless an error occurs), irrespective of whether the receive has completed.
<b>Receive</b>	<b>MPI_Recv</b>	<b>Completes when a message arrives.</b>



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

Communication modes - explained



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

FORTRAN sending syntax:

```
CALL MPI_SSEND(buf, count, datatype, dest, tag, comm,  
ierr)
```

- buf: start of data to be sent.
- count: number of elements to send (integer).
- datatype: type of data.
- dest: destination process (integer).
- tag: label to identify this instance (integer).
- comm: communicator group.
- ierr: integer error code

e.g. sending 1 integer in data to rank=2 (tag=100)

```
CALL MPI_SSEND(data, 1, MPI_INTEGER,  
2, 100, MPI_COMM_WORLD, ierr)
```



## 2 Basics of MPI

### 2.2 Point-to-point communications (cont.)

C sending syntax:

```
MPI_Ssend(void *buf, int count, MPI_Datatype datatype,  
          int dest, int tag, MPI_Comm comm)
```

- \*buf: pointer to start of data.
- count: number of elements to send.
- datatype: type of data.
- dest: destination process.
- tag: label to identify this instance of communication.
- comm: communicator group.

e.g. sending 1 integer data to rank=2 (tag =100)

```
MPI_Ssend(&data, 1, MPI_INT,  
          2, 100, MPI_COMM_WORLD);
```



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

FORTTRAN receiving syntax:

```
CALL MPI_RECV(buf, count, datatype, source, tag, comm,  
status, error)
```

- buf: starting location where data should be put
- count: number of elements to receive (integer)
- datatype: type of data
- source: sending process rank (integer)
- tag: message identifier (integer)
- comm: communicator
- status: integer array of size MPI\_STATUS\_SIZE
- error: integer error code

e.g. receiving 1 integers into data2 from rank=1 (tag=100)

```
CALL MPI_RECV(data2, 1, MPI_INT, 1, 100,  
MPI_COMM_WORLD, status, error)
```



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

C receiving syntax:

```
MPI_Recv(void *buf, int count, MPI_Datatype datatype,  
int source, int tag, MPI_Comm comm, MPI_Status *status)
```

- \*buf: pointer to start of receiving buffer
- count: number of elements to receive
- datatype: type of data
- source: sending process rank
- tag: message identifier
- comm: communicator
- \*status: pointer to message envelope

e.g. receiving 1 integers into data2 from rank=1 (tag=100)

```
MPI_RECV(&data2, 1, MPI_INT, 1, 100,  
MPI_COMM_WORLD, &status);
```





# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

C example:

```
#include <mpi.h>

int main (int argc, char *argv[]){
    int rank, size, n=5;
    int sbuf[n], rbuf[n];
    MPI_Status status;
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &size);
    MPI_Comm_rank(MPI_COMM_WORLD, &rank);

    if (rank == 0) {
        MPI_Ssend(&sbuf[0], n, MPI_INT, 1, 99, MPI_COMM_WORLD);
    }
    if (rank == 1) {
        MPI_Recv(&rbuf[0], n, MPI_INT, 0, 99, MPI_COMM_WORLD,
                &status);
    }
    MPI_Finalize();
}
```



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

FORTRAN example:

```
PROGRAM mpi
IMPLICIT NONE
INCLUDE 'mpif.h'
INTEGER :: rank, size, status(MPI_STATUS_SIZE), ierr
INTEGER, PARAMETER :: n=5
INTEGER :: sbuf(n), rbuf(n)
CALL MPI_INIT(ierr)
CALL MPI_COMM_SIZE(MPI_COMM_WORLD, size, ierr);
CALL MPI_COMM_RANK(MPI_COMM_WORLD, rank, ierr);

IF (rank .EQ. 0) THEN
    CALL MPI_SSEND(sbuf(1),n,MPI_INTEGER,1,99,MPI_COMM_WORLD,ierr)
ENDIF
IF (rank .EQ. 1) THEN
    CALL MPI_RECV(rbuf(1),n,MPI_INTEGER,0,99, &
        MPI_COMM_WORLD,status,ierr)
ENDIF

CALL MPI_FINALIZE(ierr);
END PROGRAM mpi
```



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

Wildcarding:

The receiving process can wildcard

To receive from any source:

- Set source to `MPI_ANY_SOURCE`

To receive with any tag:

- Set tag to `MPI_ANY_TAG`

Actual source and tag are returned in the receiver's status parameter.



## 2 Basics of MPI

### 2.2 Point-to-point communications (cont.)

The status communication envelope:

Like a letter there is much more information in a message than just the body text:

- Sender's address
- Reference number
- How many pages

Returned in the status parameter are:

- Source
- Tag
- Error code

It is also possible to query the received count



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

- In C, status is a structure containing three fields
- In FORTRAN, status is an array of INTs of size MPI\_STATUS\_SIZE

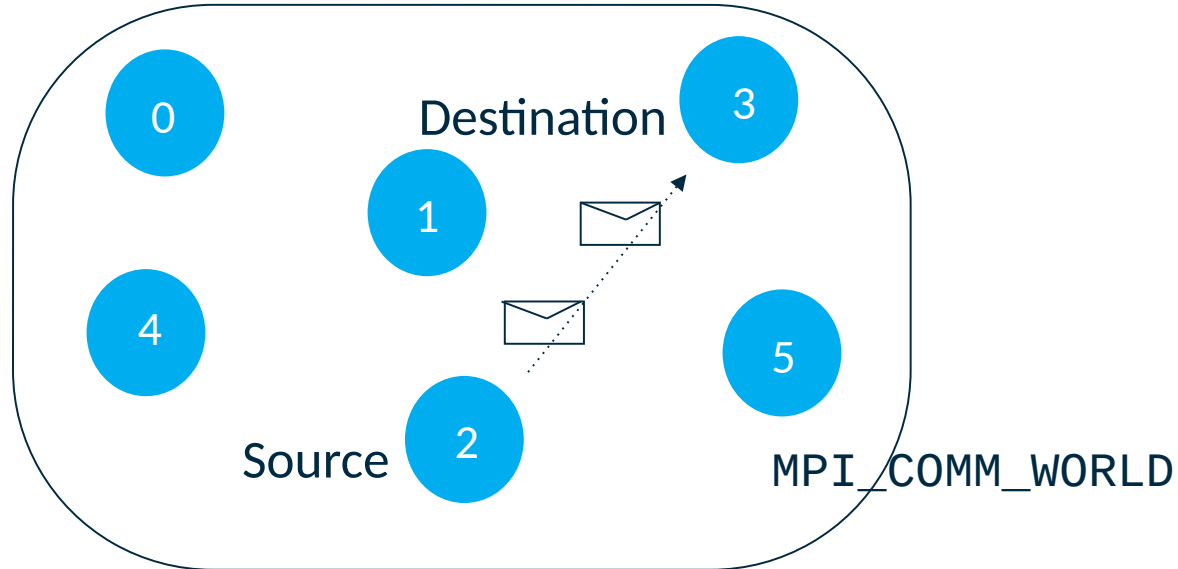
Querying the status parameter	C	FORTRAN
Source process	<code>source=status.MPI_SOURCE;</code>	<code>source=status(MPI_SOURCE)</code>
Tag	<code>tag=status.MPI_TAG;</code>	<code>tag=status(MPI_TAG)</code>
Error code	<code>error=status.MPI_ERROR;</code>	<code>error=status(MPI_ERROR)</code>
Count	<code>MPI_Get_count(&amp;status, MPI_datatype, &amp;count);</code>	<code>MPI_GET_COUNT(status, MPI_datatype, count, ierr)</code>



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

The order of messages is preserved:

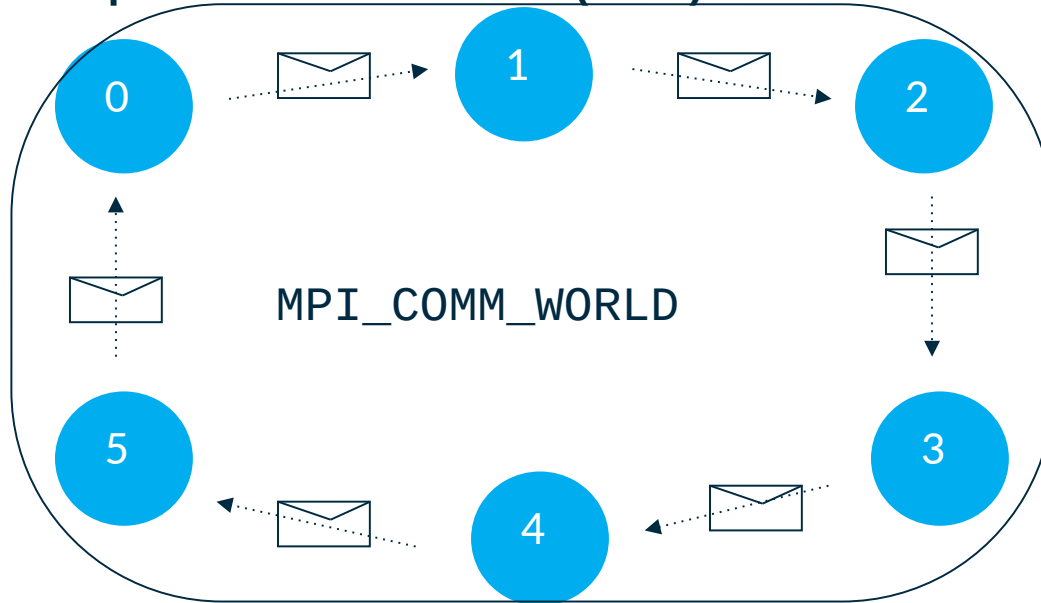


- Messages do not overtake each other.
- This is also true for non-synchronous (buffered) sends.



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)



**Deadlock**



- **Deadlock** occurs if all processes post a synchronous send before a receive operation.
- All processes will hang or 'deadlock', waiting for a receive that has never been posted.

# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

Deadlock avoidance: carry out non-blocking communication

Sending process	Receiving process
Initiate send, non-blocking (MPI_Issend)	Initiate receive, non-blocking (MPI_Irecv)
Perform other tasks	Perform other tasks
Wait for completion (MPI_Wait)	Wait or test for completion (MPI_Test)

Relies upon a 'request' handle

- Allocated when a communication is initiated.
- Can be queried to test whether non-blocking operation has been completed.
- A non-blocking call followed by an explicit wait, is identical to the blocking communication.





## 2 Basics of MPI

### 2.2 Point-to-point communications (cont.)

Deadlock avoidance 2:

`MPI_Send` and `MPI_Recv` can be carefully ordered to avoid deadlocks. This can be difficult and time consuming.

MPI also provides a very useful *combined* send and receive function, `MPI_Sendrecv`, which is guaranteed not to deadlock.

- This routine sends a message and posts a receive, then blocks until the send data buffer is free and the receive data buffer has received its data.



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

### MPI\_Sendrecv

C:

```
int MPI_Sendrecv( void *sendbuf, int sendcount, MPI_Datatype  
sendtype, int destination, int sendtag, void *recvbuf, int  
recvcount, MPI_Datatype recvtype, int source, int recvtag,  
MPI_Comm comm, MPI_Status &status);
```

FORTTRAN:

```
REAL sendbuf(*)  
REAL recvbuf(*)  
INTEGER sendcount, dest, sendtag  
INTEGER recvcount, source, recvtag  
INTEGER comm, status(MPI_STATUS_SIZE), ierr
```

```
CALL MPI_SENDRECV(sendbuf[1], sendcount, MPI_REAL, dest,  
sendtag, recvbuf[1], recvcount, MPI_REAL, source, recvtag,  
comm, status, ierr)
```



# 2 Basics of MPI

## 2.2 Point-to-point communications (cont.)

### MPI\_Sendrecv

- MPI\_PROC\_NULL can be specified instead of the rank of the source or the destination
  - Useful for doing non-circular shifts with MPI\_Sendrecv
- A message sent by MPI\_Sendrecv can be received by a regular receive operation
- A message sent by a regular send can be received by MPI\_Sendrecv
- The send and receive buffers must not overlap
  - If you want to use the same buffer for both the send and receive, use MPI\_Sendrecv\_replace



# Practical 1: point-to-point communications

## 1. Node pair communication

- Write a program in which two processes repeatedly pass a message (e.g. a random integer) back and forth, altering the message along the way.
- Template:  
`exercises/practical1/PingPong.c`  
`exercises/practical1/PingPong.f90`

## 2. Bonus exercise: cycling communication

- Modify the node pair communication program so that several processes pass a message around the group, printing at each stage.
- Perform a simple mathematical alteration of the message on each process and populate an array across the nodes with the data.



# Practical 1: Review

The principles of node pair communication

```
send = 8 /* Initialise send buffer */
      Loop 100 times /* repeat for 100 iterations */

      On Processor 1 {
/* blocking send on first processor to second */
      MPI_Ssend(send,1,MPI_INT, 1, 1, MPI_COMM_WORLD);
/* blocking receive on first processor from second */
      MPI_Recv(recv,1,MPI_INT, 1, 2, MPI_COMM_WORLD, &status);
      send = recv + 1;
      } whilst on Processor 2 {
/* blocking receive on second processor from first */
      MPI_Recv(recv,1,MPI_INT, 0, 1, MPI_COMM_WORLD, &status);
      send = recv + 1;
/* blocking send on first processor to second */
      MPI_Ssend(send,1,MPI_INT, 0,2,MPI_COMM_WORLD);
      }
}
```

For the complete answers, please consult the solutions:  
solutions2/



# 2 Basics of MPI

## 2.3 Collective communications

Introduction & characteristics

Barrier Synchronisation

Broadcast

Scatter

Gather

Global reduction operations

- Predefined operations
- User-defined operations

Partial sums



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

Collective communication involves a group of processes.

Called by *all* processes in a communicator.

Examples:

- Broadcast, scatter, gather (Data Distribution)
- Global sum, global maximum, etc. (Reduction Operations)
- Barrier synchronisation

Characteristics

- Collective communication will not interfere with point-to-point communication and vice-versa.
- All processes must call the collective routine.
- Synchronization not guaranteed (except for barrier)
- No non-blocking collective communication
- No tags

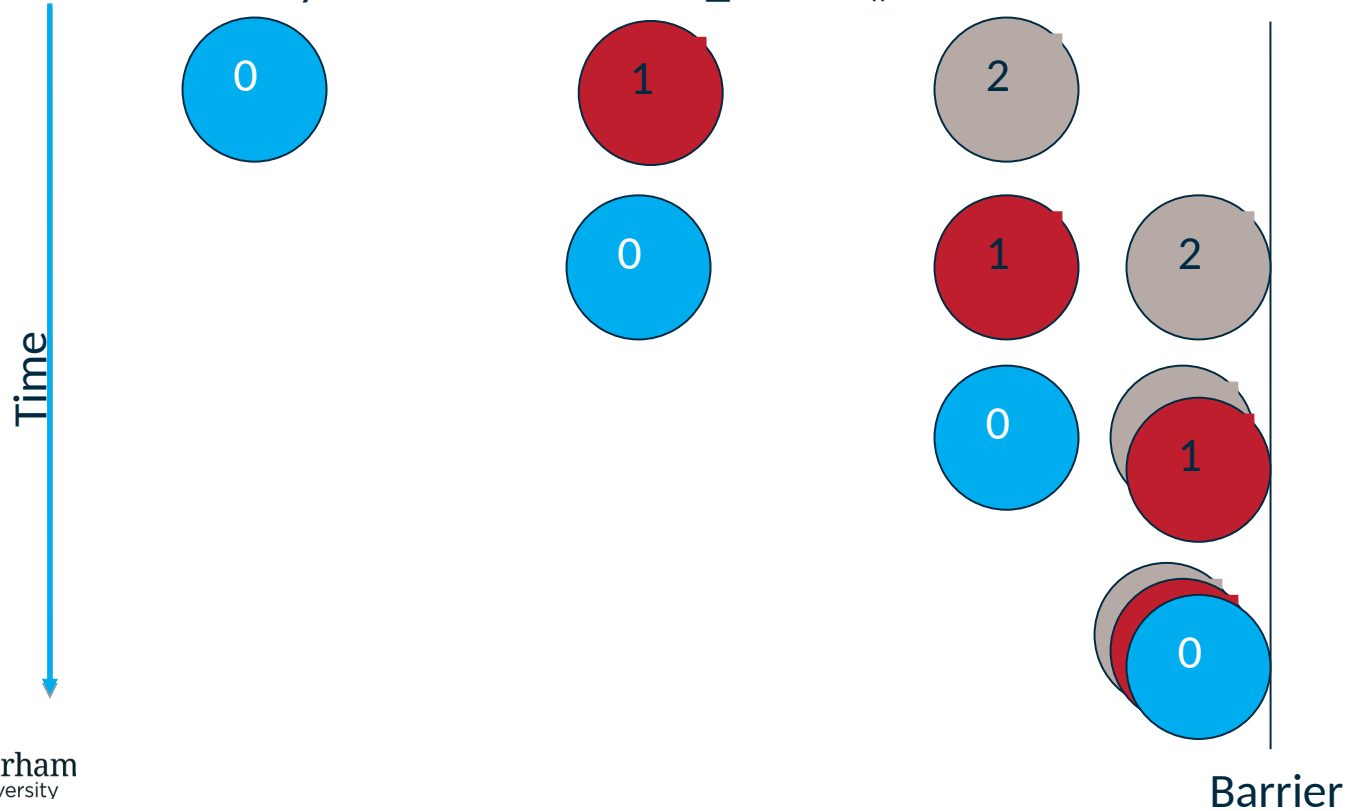
Receive buffers must be exactly the right size



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

Barrier Synchronisations: MPI\_Barrier()





# 2 Basics of MPI

## 2.3 Collective communications (cont.)

### Barrier Synchronisation

Each processes in communicator waits at barrier until all processes encounter the barrier.

Fortran:

```
INTEGER comm, error  
CALL MPI_BARRIER(comm, error)
```

C:

```
MPI_Barrier(MPI_Comm comm);
```

Note:

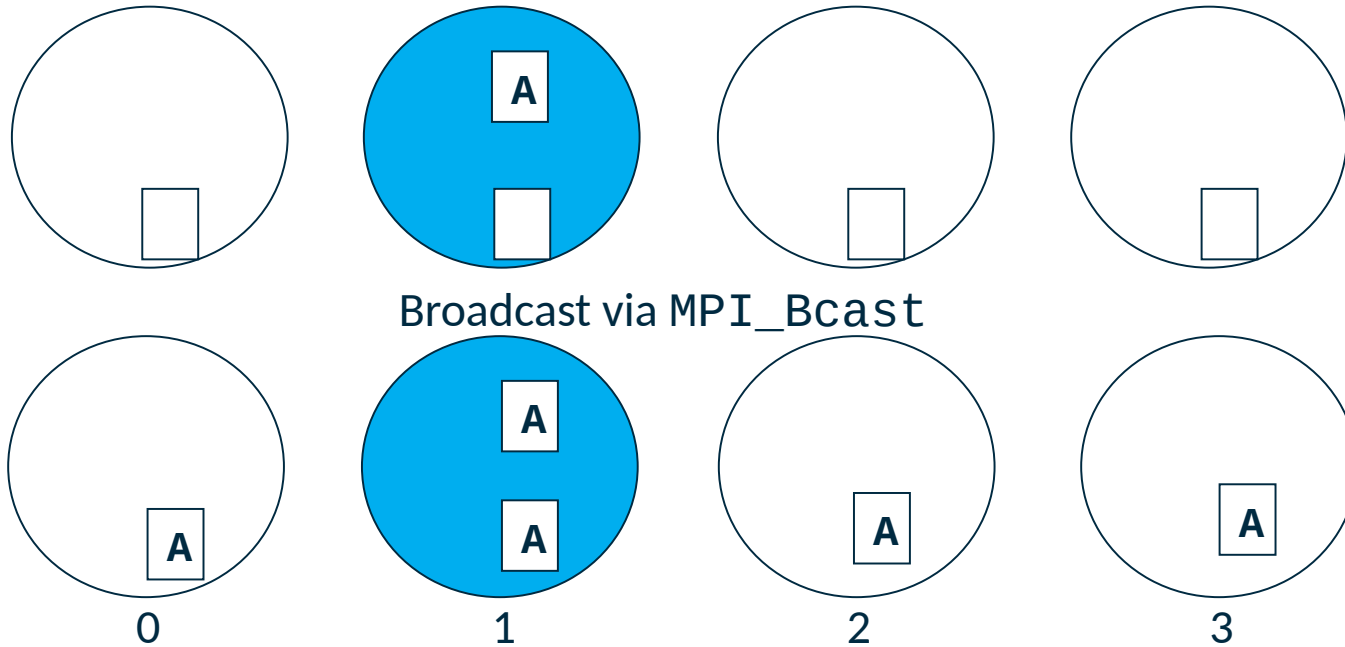
Barrier calls are exceptionally useful for avoiding 'racing' issues, where one processor can race ahead of the others and set up deadlock.



## 2 Basics of MPI

### 2.3 Collective communications (cont.)

Broadcasting: duplicates data from one process to all other processes in communicator group



As with all collective processes, must be called simultaneously by every process

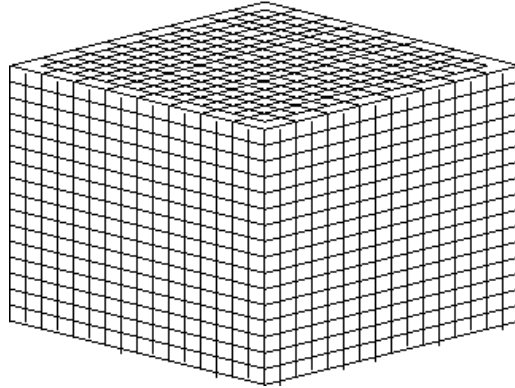


## 2 Basics of MPI

### 2.3 Collective communications (cont.)

*Recall our fluid dynamics example...*

- Each cell in the domain



has to be advanced in time by the same amount – the *timestep*.

This timestep could be ‘broadcast’ by a master processor.



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

Broadcast syntax:

Fortran:

```
INTEGER count, datatype, root, comm, ierr  
CALL MPI_BCAST(buffer[1],count,datatype,root,comm,ierr)
```

C:

```
MPI_Bcast (void *buffer, int count, MPI_Datatype  
datatype, int root, MPI_Comm comm);
```

- e.g broadcasting deltat from rank 0 to the entire group:

```
double deltat;  
MPI_Bcast(deltat, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
```



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

Multiple data gathering and scattering routines exist

- `MPI_Scatter` – scatters data from a single process to all processes
- `MPI_Gather` – gathers data from all processes to a single process
- `MPI_Allgather` – each process receives a copy of the gathered data.
- `MPI_Alltoall` – gathers data and scatters (possibly different) data from all to all processes - very much the basis of parallelized Fourier transforms
  - Note: this command can be very taxing for the interconnection, sending multiple small messages between all processes. It seems particularly demanding on the newest variety of architecture with ~128 cores in a dual-CPU node.
- Gather/scatter with varying amount of data on each process
  - `MPI_GATHERV`, `MPI_SCATTERV`, `MPI_ALLGATHERV`, `MPI_ALLTOALLV`



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

### Global Reduction operations

- Compute a result involving data distributed over a group of processes.
- Suppose that each process  $i$  has computed a number  $X_i$  and that the result needed  $X$  is the sum of these. This global sum is an example of a *reduction operation*.
- In MPI, a set of binary reduction operations are defined for predefined MPI data types.
  - All binary operations are assumed to be associative:  $(x*y)*z = x*(y*z)$
  - All the predefined binary operations are also commutative:  $x*y = y*x$ 
    - It is possible to define non-commutative binary operations.
- The order in which the reduction is done is unspecified. MPI guarantees the result will only be the same to within round-off errors.



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

MPI name	Function	C	FORTTRAN
MPI_MAX	Maximum		MAX(a <sub>1</sub> ... ..a <sub>n</sub> )
MPI_MIN	Minimum		MIN(a <sub>1</sub> ... ..a <sub>n</sub> )
MPI_SUM	Sum	+	+
MPI_PROD	Product	*	*
MPI_LAND	Logical AND	&&	.AND.
MPI_BAND	Bitwise AND	&	
MPI_LOR	Logical OR		.OR.
MPI_BOR	Bitwise OR		
MPI_LXOR	Logical exclusive OR	!=	.NEQV.
MPI_BXOR	Bitwise exclusive OR	^	
MPI_MAXLOC	Maximum and location		
MPI_MINLOC	Minimum and location		

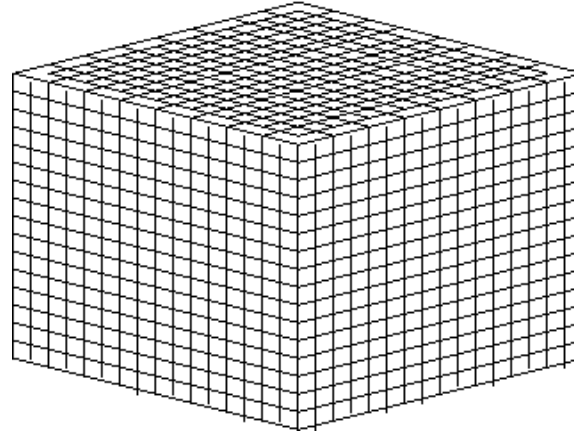


# 2 Basics of MPI

## 2.3 Collective communications (cont.)

*Recalling our fluid dynamics example...*

- Each cell in the domain



has to be advanced in time by the *timestep*.

Each processor can calculate its own timestep based on its section and then the minimum of all these values is used as the global timestep.





# 2 Basics of MPI

## 2.3 Collective communications (cont.)

`MPI_Allreduce`: Combines values from all processes and distributes the result back to all processes. Function syntax:

Fortran

```
INTEGER count, type, count, rtype, comm, error  
CALL MPI_ALLREDUCE(sbuf[1], rbuf[1], count, rtype, op, comm, error)
```

C:

```
MPI_Allreduce(void *sbuf, void *rbuf, int count, MPI_Datatype  
    datatype, MPI_Op op, MPI_Comm comm);
```

For example, in our CFD case:

```
MPI_Allreduce(deltat, deltat_global_min, 1,  
    mpi_real, MPI_MIN, MPI_COMM_WORLD, ierr)
```



# 2 Basics of MPI

## 2.3 Collective communications (cont.)

MPI\_Scan: Computes the scan (partial reductions) of data on a collection of processes.  
Function syntax:

Fortran:

```
REAL sendbuf(*), recvbuf(*)  
INTEGER count, type, count, rtype, comm, error  
CALL MPI_SCAN(sendbuf, recvbuf, count, datatype, op, comm, ierr)
```

C:

```
MPI_Scan(const void *sendbuf, void *recvbuf, int count,  
MPI_Datatype datatype, MPI_Op op, MPI_Comm comm);
```



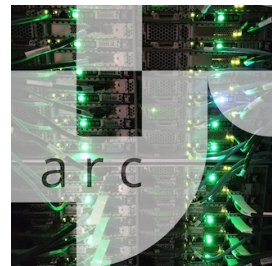
# Practical 2: collective communications

## 1. Collective communication with MPI\_Allreduce

- Compute the global sum of all ranks of the processes using MPI global reduction
- Template:  
`exercises/practical2/collective.c`  
`exercises/practical2/collective.f90`

## 2. Collective communication with MPI\_Scan

- Rewrite the previous program so that each process computes a partial rank sum
- Additional task: make sure that the output is in natural order



# 3 Basics of OpenMP

- OpenMP allows independent units of work to be done by each of the processors on your system
- OpenMP uses a so-called ***‘fork and join’*** model, i.e., the code executes ***serially*** until it hits a ***parallel region*** where the code is parallelised across threads
- We call this ***shared memory parallelism*** since all the processor threads on one system have access to the same memory block
- No need for communication like with MPI as values can be read from a common register
- OpenMP is included as a library, though it must be flagged at compile time

**C**

```
#include <omp.h>
```

**Fortran**

```
use omp_lib
```



# 3 Basics of OpenMP

The fundamental building block of OpenMP is the parallel region:

**C**

```
#pragma omp parallel{  
    // code goes here  
}
```

**Fortran**

```
!$omp parallel  
    ! code goes here  
!$omp end parallel
```

Multithreading isn't magic! We have numerous problems, such as:

- **Expensive** to spawn new threads
- Can be difficult to share work evenly across threads – **load imbalance**
- Run into problems like **race conditions** if not careful
- Much easier to run into **segmentation faults**, if we don't take care around critical tasks such as writing to files or particular memory addresses



# 3 Basics of OpenMP

## 3.1 Pragma directives

- The **pragmas** and **directives** that we use to define parallel regions are typically written as **#pragma omp parallel [clause]** or **!\$omp parallel [clause]** in which **[clause]** defines certain qualities of the parallel regions, e.g.,

```
#pragma omp parallel num_threads(4) {  
    // code here is ran in parallel by 4 threads  
}
```

- Within a parallel section, we can also indicate that only one thread should perform some code, by stating **#pragma omp single**
- Within a parallel section, we can also indicate that only the master thread should perform some code, by stating **#pragma omp master**
- The number of threads can also be set by the environment variable:

```
export OMP_NUM_THREADS=4
```



# 3 Basics of OpenMP

## 3.2 Parallel regions

```
int main(){
    #pragma omp parallel num_threads(4){
        foo();
    #pragma omp single
        bar();
    }
}
void foo(){
    printf("function foo, using thread number%d\n", omp_get_thread_num());
}
void bar(){
    printf("function bar, using thread number%d\n", omp_get_thread_num());
}
```

function foo, using thread number 1  
function bar, using thread number 1  
function foo, using thread number 0  
function foo, using thread number 3  
function foo, using thread number 2



# 3 Basics of OpenMP

## 3.3 Parallel for

- Most parallelism will be achieved with **parallel for** (C) or **parallel do** (Fortran)

### C

```
#pragma omp parallel for  
for (int i=0; i<100; i++){  
    // code goes here  
}
```

### Fortran

```
!$omp parallel do  
do i = 1, 100  
    ! code goes here  
end do  
!$omp end parallel do
```

- With no clauses, the loop iterations are split up as equally as possible between the threads
- Can also append this with **schedule(static, chunksize)** to give each thread **chunksize** parts to do before assigning work to the next thread
- Can use dynamic scheduling, but this hinders at runtime





# 3 Basics of OpenMP

## Example: scheduling

- We will now work through the

[BasicParallelProgramming/omp/examples/scheduling](#)

completed example

- This example shows the basics of parallel for loops along with scheduling of the loop
- The first loop shows a standard OpenMP parallelised loop
- The second loop shows a scheduled parallel loop, with static scheduling and a chunksize of 2



# 3 Basics of OpenMP

## 3.4 Simplest Parallelism

- The simplest form of parallelism is a series of operations that are **independent** of each other
- Consider two arrays  $b$  and  $c$  of the same length, and the following code

```
for (int i = 0; i < N; i++){  
    a[i] = b[i] + c[i]  
}
```

- Each of these operations is **independent** of one another.
- No two memory addresses are **read from** or **written to** during this process
- We can modify it as such:

```
#pragma omp parallel for  
for (int i = 0; i < N; i++){  
    a[i] = b[i] + c[i]  
}
```

- Though typical real world examples are more complex!



# 3 Basics of OpenMP

## 3.5 Variable Sharing

- By default, all variables are shared between threads (and can be modified!), so in many circumstances, variables should be marked **private**
- Variables marked **private** will be newly copied to each thread, and only modifiable by that thread (increasing computational cost!). Note that the default constructor will be used (i.e. a double marked **private** will be 0 inside a parallel region)
- Variables marked **firstprivate** will again by newly constructed, but will copy the original value
- The safest way to do this is to specify **default(none)**

```
double x = 9;
const double a = 10;
double b = 11;
#pragma omp parallel private(x) shared(a) firstprivate(b) default(none)
{
    printf("%F", x); // prints 0
    printf("%F", a); // prints 10
    printf("%F", b); // prints 11
}
```



# 3 Basics of OpenMP

## 3.6 Race Conditions

- What do you expect to happen in the following code:

```
int sum = 0;
for (int i = 1; i <= 10; i++){
    sum += i;
}
```

- What about in this instead?

```
int sum = 0;
#pragma omp parallel for
for (int i = 1; i <= 10; i++){
    sum += i;
}
```



# 3 Basics of OpenMP

## 3.6 Race Conditions (cont.)

We don't get the desired result! This is because updating **sum** consists of three operations:

- 1) Read sum
- 2) Update sum ( $\text{sum} \rightarrow \text{sum}+1$ )
- 3) Store the new sum

If thread 0 reads **sum** to be 5, just before thread 1 stores it to be 7, we will get the wrong result!



# 3 Basics of OpenMP

## 3.6 Race Conditions (cont.)

The solution is using **reduction**:

- Each thread gets a subset of the data to compute, and combines at the end, using the operation we specify
- The syntax is **reduction(operation : variable)**. Supports operations like “+”, “-”, “\*”
- You can add multiple reduction statements

```
int sum = 0;
#pragma omp parallel for reduction(+ : sum)
for (int i = 1; i <= 10; i++){
    sum += i;
}
```



# 3 Basics of OpenMP

## 3.6 Race Conditions (cont.)

We can alternatively use a directive such as **atomic** or **critical** to indicate that only one thread at a time can perform a certain step, but this hinders performance

This forces each thread to wait for the others defeats the point of using multiple threads

```
int sum = 0;
#pragma omp parallel for
for (int i = 1; i <= 10; i++){
    #pragma omp critical
    sum += i;
}
```



# 3 Basics of OpenMP

## Example: race conditions

- We will now work through the

[BasicParallelProgramming/omp/examples/raceConditions](#)

completed example

- This example is summing the first 10 integers with various parallelisms
- First, no parallelism. Correct!
- Second, naively parallelise the loop. Incorrect!
- Third, use a critical to avoid the race condition. Correct but slow!
- Finally, use a reduction operation. Correct and performant!





# 3 Basics of OpenMP

## Practical: race conditions

- Have a go at the

[BasicParallelProgramming/omp/practicals/factorial](#)

practical

- The practical includes a serial version of calculation a factorial:  $n! = n \times (n-1) \times (n-2) \times \dots \times 1$ , e.g.,  $4! = 4 \times 3 \times 2 \times 1$
- The aim is to write a parallel version of this function but be careful about race conditions!



# 3 Basics of OpenMP

## 3.7 Tasks

Tasks are a new form of parallelism that allow for execution of arbitrary code blocks

- We specify a task with **#pragma omp task**
- Each task is placed on a **pool** and picked up by a thread when there is one available. This can be good for reducing CPU idle time
- Since every thread runs each piece of code within a parallel region, we can ensure our tasks are only spawned once by using the **master** directive
- We can force execution to wait until the tasks are finished with a simple **barrier**

```
#pragma omp parallel {  
  
    // code goes here  
    #pragma omp master {  
  
        #pragma omp task  
        foo();  
  
        #pragma omp task  
        bar();  
    }  
    #pragma omp taskwait  
}  
}
```



# 3 Basics of OpenMP

## Example: tasks

- We will now work through the

[BasicParallelProgramming/omp/examples/tasks](#)

completed example

- This example shows some different ways that task parallelism can be used to build quite complex parallel workflows
- The print statements indicate which threads are running which code block



# 3 Basics of OpenMP

## Practical: calculation pi

- Have a go at the

[BasicParallelProgramming/omp/practicals/piCalc](#)

practical

- This example uses a method for computing the mathematical constant  $\pi = 3.1415926535...$
- The practical includes a serial version, which you can parallelise. Why not try different parallelism as used in the Mandelbrot set example:

[BasicParallelProgramming/omp/practicals/mandelBrot](#)



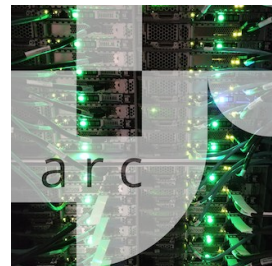
# A. Advanced topics (part I)

- I/O using MPI-IO
  - The best idea is just to use libraries built using MPI-IO: Parallel HDF5 (parallel IO in the HDF format), NetCDF (network Common Data Form)
- Cartesian Topologies
  - Create with `MPI_Cart_create`; translate rank into coordinates with `MPI_Cart_coords`; locate neighbours in every direction with `MPI_Cart_shift`
- Derived data types
  - Construct data types with `MPI_Type_contiguous`, `MPI_Type_vector`, etc.; commit with `MPI_Type_commit`; free with `MPI_Type_free`
- User-defined operations
  - Bind a user-defined operation `MPI_Op_create`; free after use with `MPI_Op_free`



# A. Advanced topics (part II)

- Creating new communicators
  - Split an existing communicator into multiple non-overlapping communicators `MPI_Comm_split`; create a duplicate of a communicator `MPI_Comm_dup`
  - Subdivide a communicator using process groups – extract the process group associated with the input communicator `MPI_Comm_group`; make a new group from selected members or by manipulating groups (see below); form a communicator based on the input group `MPI_Comm_create` (or a newer, more efficient, `MPI_Comm_create_group`)
  - Create new groups – `MPI_Group_union`, `MPI_Group_intersection`, `MPI_Group_difference`, `MPI_Group_incl`, `MPI_Group_excl`, ...
  - Free groups and communicators `MPI_Group_free` and `MPI_Comm_free`



## B. Some libraries using MPI

- Numerical libraries
  - BLACS – Basic Linear Algebra Communication Subprograms (<http://www.netlib.org/blacs/>)
  - PBLAS – Parallel Basic Linear Algebra Subprograms ([http://www.netlib.org/scalapack/pblas\\_qref.html](http://www.netlib.org/scalapack/pblas_qref.html))
  - ScaLAPACK – Scalable Linear Algebra PACKage (<http://www.netlib.org/scalapack/>)
  - FFTW – “Fastest Fourier Transform in the West” (<http://www.fftw.org/>)
  - NAG Parallel Library (<https://www.nag.com/content/nag-mpi-parallel-library>)
  - PETSC – Portable, Extensible Toolkit for Scientific Computation (<https://petsc.org>)
  - deal.II – Differential Equations Analysis Library (<https://www.dealii.org/>)



## B. Some useful advice for programming on MPI

- Adding MPI can destroy a code
  - Always maintain a serial version so its possible to compile and run serial and parallel versions and compare output
- To ease clarity, separate out communication routines
  - Separate file
  - Dummy library for serial code
  - Avoids explicit MPI references in main code
- It's possible to do most things with only MPI\_Send and MPI\_Recv if portability is a great concern
  - Collective routines (MPI\_Gather, MPI\_Bcast, MPI\_Scatter) are often better optimised than writing your own versions
- Parallel debugging can be hard. With **gdb**, the following opens `<NP>` xterminals, in each of them, you'll need to type `run` to begin executing:
  - `mpirun -np <NP> xterm -e gdb ./program`







Durham  
University

# That's it! Good luck writing your own parallel code!

## Thank you!

Feedback

<https://forms.office.com/e/hQ0Ni5brPU?origin=lprLink>

Email: [arc@durham.ac.uk](mailto:arc@durham.ac.uk)

RSE team: [arc-rse@durham.ac.uk](mailto:arc-rse@durham.ac.uk)

Web: <https://www.dur.ac.uk/arc/>

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