MPI topic: Functional parallelism

Experimental html version of downloadable textbook, see http://www.tacc.utexas.edu/~eijkhout/istc/istc.html

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2 MPI topic: Functional parallelism

2.1 The SPMD Model

MPI programs conform largely to the *SPMD* model, where each processor runs the same executable. This running executable we call a *process* .

When MPI was first written, 20 years ago, it was clear what a processor was: it was what was in a computer on someone's desk, or in a rack. If this computer was part of a networked cluster, you called it a *node* . So if you ran an MPI program, each node would have one MPI process;

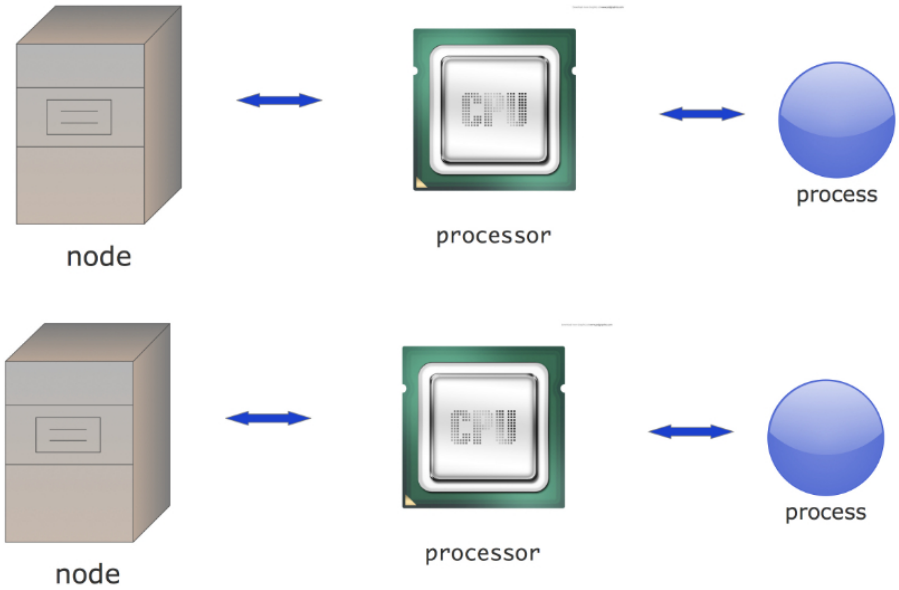
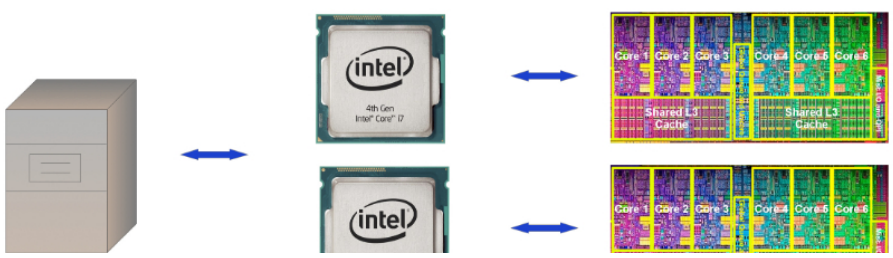


FIGURE 2.1: Cluster structure as of the mid 1990s

figure 2.1 . You could of course run more than one process, using the *time slicing* of the *OS* , but that would give you no extra performance.

These days the situation is more complicated. You can still talk about a node in a cluster, but now a node can contain more than one processor chip (sometimes called a *socket*), and each processor chip probably has multiple *cores* .



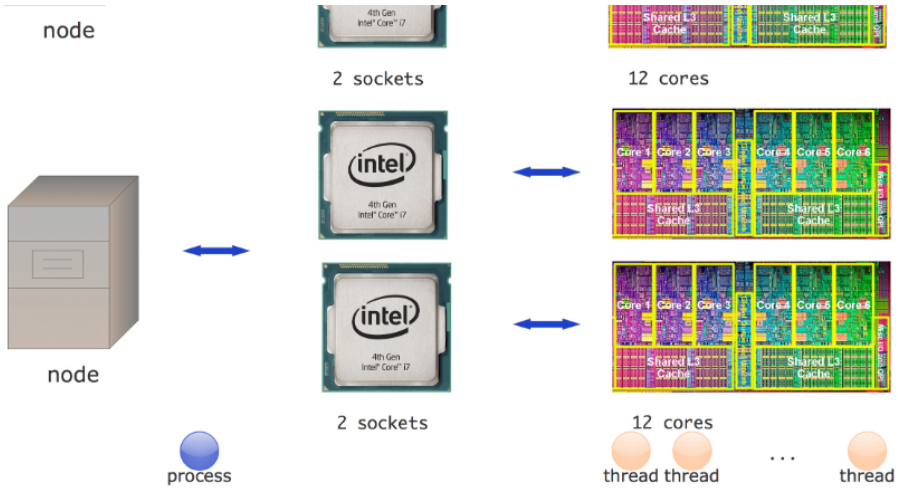


FIGURE 2.2: Hybrid cluster structure

Figure 2.2 shows how you could explore this using a mix of MPI between the nodes, and a shared memory programming system on the nodes.

However, since each core can act like an independent processor, you can also have multiple MPI processes per node. To MPI, the cores look like the old completely separate processors. This is the `pure MPI' model of figure 2.3 , which we will use in most of this part of the book. (Hybrid computing will be discussed in chapter Hybrid computing .)

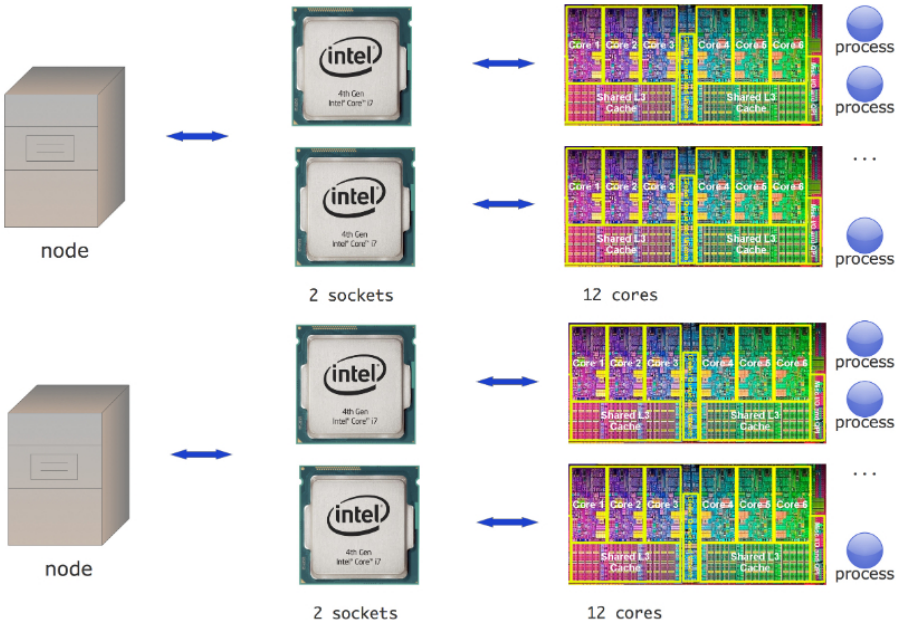


FIGURE 2.3: MPI-only cluster structure

This is somewhat confusing: the old processors needed MPI programming, because they were physically separated. The cores on a modern processor, on the other hand, share the same memory, and even some caches. In its basic mode MPI seems to ignore all of this: each core receives an MPI process and the programmer writes the same send/receive call no matter where the other process is located. In fact, you can't immediately see whether two cores are on the same node or different nodes. Of course, on the implementation level MPI uses a different communication mechanism depending on whether cores are on the same socket or on different nodes, so you don't have to worry about lack of efficiency.

Remark

In some rare cases you may want to run in an *MPMD* mode, rather than *SPMD* . This can be achieved either on the *OS* level (see section 14.8.4), using options of the *mpiexec* mechanism, or you can use MPI's built-in process management; chapter MPI topic: Process management . Like I said, this concerns only rare cases.

2.2 Starting And Running MPI Processes

crumb trail: > mpi-functional > Starting and running MPI processes

The *SPMD* model may be initially confusing. Even though there is only a single source, compiled into a single executable, the parallel run comprises a number of independently started MPI processes (see section 1.3 for the mechanism).

The following exercises are designed to give you an intuition for this one-source-many-processes setup. In the first exercise you will see that the mechanism for starting MPI programs starts up independent copies. There is nothing in the source that says `and now you become parallel'.

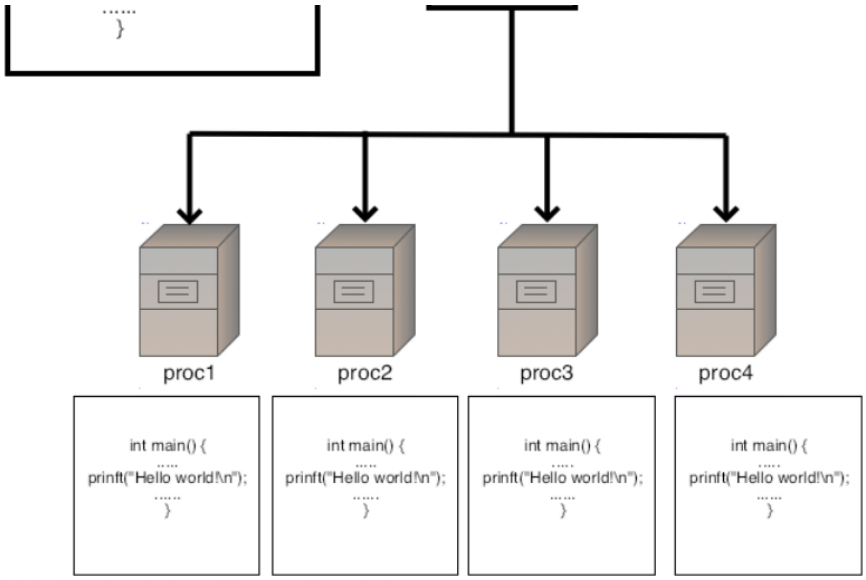


FIGURE 2.4: Running a hello world program in parallel

The following exercise demonstrates this point.

Exercise
Write a `hello world' program, without any MPI in it, and run it in parallel with `mpiexec` or your local equivalent. Explain the output.

(On TACC machines such as stampede, use `ibrun` , no processor count.)

This exercise is illustrated in figure 2.4 .

2.2.1 Headers

crumb trail: > mpi-functional > Starting and running MPI processes > Headers

If you use MPI commands in a program file, be sure to include the proper header file, *mpi.h* or *mpif.h* .

```
#include "mpi.h" // for C
#include "mpif.h" ! for Fortran
```

For *Fortran90* , many MPI installations also have an MPI module, so you can write

```
use mpi     ! pre 3.0
use mpi_f08 ! 3.0 standard
```

The internals of these files can be different between MPI installations, so you can not compile one file against one `mpi.h` file and another file, even with the same compiler on the same machine, against a different MPI.

Python note
It's easiest to

```
from mpi4py import MPI
```

To compile MPL programs, add a line

```
#include <mpl/mpl.hpp>
```

to your file.

2.2.2 Initialization / Finalization

crumb trail: > mpi-functional > Starting and running MPI processes > Initialization / finalization

Every (useful) MPI program has to start with *MPI initialization* through a call to *MPI_Init*

> Routine reference: MPI_Init

, and have *MPI_Finalize*

> Routine reference: MPI_Finalize

to finish the use of MPI in your program. The init call is different between the various languages.

In C, you can pass `argc` and `argv` , the arguments of a C language main program:

```
int main(int argc,char **argv) {
    ....
    return 0;
}
```

(It is allowed to pass `NULL` for these arguments.)

Fortran (before 2008) lacks this commandline argument handling, so *MPI_Init* lacks those arguments.

Python note
There are no initialize and finalize calls: the `import` statement performs the initialization.

There is no initialization or finalize call.

UNKNOWN Initialization is done at the first `mpl::environment` method call, such as `comm_world` .

This may look a bit like declaring `this is the parallel part of a program', but that's not true: again, the whole code is executed multiple times in parallel.

Exercise
Add the commands *MPI_Init* and *MPI_Finalize* to your code. Put three different print statements in your code: one before the init, one between init and finalize, and one after the finalize. Again explain the output.

Run your program on a large scale, using a batch job. Where does the output go? Experiment with

```
MY_MPIRUN_OPTIONS="-prepend-rank" ibrun yourprogram
```

Remark
For hybrid MPI-plus-threads programming there is also a call *MPI_Init_thread* . For that, see section 39.2 .

2.2.2.1 Aborting an MPI run

Apart from *MPI_Finalize* , which signals a successful conclusion of the MPI run, an abnormal end to a run can be forced by *MPI_Abort*

> Routine reference: MPI_Abort

. This aborts execution on all processes associated with the communicator, but many implementations simply abort all processes. The `value` parameter is returned to the environment.

2.2.2.2 Testing the initialized/finalized status

The commandline arguments `argc` and `argv` are only guaranteed to be passed to process zero, so the best way to pass commandline information is by a broadcast (section 3.3.3).

There are a few commands, such as *MPI_Get_processor_name* , that are allowed before *MPI_Init* .

If MPI is used in a library, MPI can have already been initialized in a main program. For this reason, one can test where *MPI_Init* has been called with *MPI_Initialized*

> Routine reference: MPI_Initialized

.

You can test whether *MPI_Finalize* has been called with *MPI_Finalized*

> Routine reference: MPI_Finalized

.

2.2.2.3 Information about the run

Once MPI has been initialized, the *MPI_INFO_ENV* object contains a number of key/value pairs describing run-specific information; see section 14.1.1.1 .

2.2.2.4 Commandline arguments

The *MPI_Init* routines takes a reference to `argc` and `argv` for the following reason: the *MPI_Init* calls filters out the arguments to *mpirun* or *mpiexec* , thereby lowering the value of `argc` and elimitating some of the `argv` arguments.

On the other hand, the commandline arguments that are meant for `mpiexec` wind up in the *MPI_INFO_ENV* object as a set of key/value pairs; see section 14.1.1 .

2.3 Processor Identification

Since all processes in an MPI job are instantiations of the same executable, you'd think that they all execute the exact same instructions, which would not be terribly useful. You will now learn how to distinguish processes from each other, so that together they can start doing useful work.

2.3.1 Processor Name

In the following exercise you will print out the hostname of each MPI process with *MPI_Get_processor_name*

> Routine reference: MPI_Get_processor_name

as a first way of distinguishing between processes.

Exercise
Now use the command *MPI_Get_processor_name* in between the init and finalize statement, and print out on what processor your process runs. Confirm that you are able to run a program that uses two different nodes.

The character buffer needs to be allocated by you, it is not created by MPI, with size at least *MPI_MAX_PROCESSOR_NAME* .

TACC nodes have a hostname `cRRR-CNN` , where RRR is the rack number, C is the chassis number in the rack, and NN is the node number within the chassis. Communication is faster inside a rack than between racks!

The character storage is provided by the user: the character array must be at least *MPI_MAX_PROCESSOR_NAME* characters long. The actual length of the name is returned in the `resultlen` parameter.

The *processor_name* returning a `std::string` :

```
std::string mpl::environment::processor_name ();
```

2.3.2 Communicators

First we need to introduce the concept of *communicator* , which is an abstract description of a group of processes. For now you only need to know about the existence of the *MPI_Comm* data type, and that there is a pre-defined communicator *MPI_COMM_WORLD* which describes all the processes involved in your parallel run.

In the procedural languages C, a *communicator* is a *variable* that is passed to most routines:

```
#include <mpi.h>
MPI_Comm comm = MPI_COMM_WORLD;
MPI_Send( /* stuff */ comm );
```

Fortran note
In Fortran, pre-2008 a communicator was an *opaque handle* , stored in an `Integer` . With *Fortran 2008* , communicators are derived types:

```
use mpi_f08
Type(MPI_Comm} :: comm = MPI_COMM_WORLD
call MPI_Send( ... comm )
```

Python note
In object-oriented languages, a communicator is an *object* , and rather than passing it to routines, the routines are often methods of the communicator object:

```
from mpi4py import MPI
comm = MPI.COMM_WORLD
comm.Send( buffer, target )
```

The naive way of declaring a communicator would be:

> C++ Code: mplcommcopy

calling the predefined environment method *comm_world*

However, if the variable will always correspond to the world communicator, it is better to make it `const` and declare it to be a reference:

> C++ Code: mplcommref

The communicator class has its copy operator deleted; however, copy initialization exists:

> C++ Code: mplcompare

(This outputs true/false/false respectively.)

UNKNOWN
The copy initializer performs an *MPI_Comm_dup* .

Pass communicators by reference to avoid communicator duplication:

> C++ Code: mplcommpass

You will learn much more about communicators in chapter MPI topic: Communicators .

2.3.3 Process And Communicator Properties: Rank And Size

To distinguish between processes in a communicator, MPI provides two calls

1. *MPI_Comm_size*

   Routine reference: MPI_Comm_size

   reports how many processes there are in all; and
2. *MPI_Comm_rank*

   Routine reference: MPI_Comm_rank

   states what the number of the process is that calls this routine.

If every process executes the *MPI_Comm_size* call, they all get the same result, namely the total number of processes in your run. On the other hand, if every process executes *MPI_Comm_rank* , they all get a different result, namely their own unique number, an integer in the range from zero to the number of processes minus 1. See figure 2.5 .

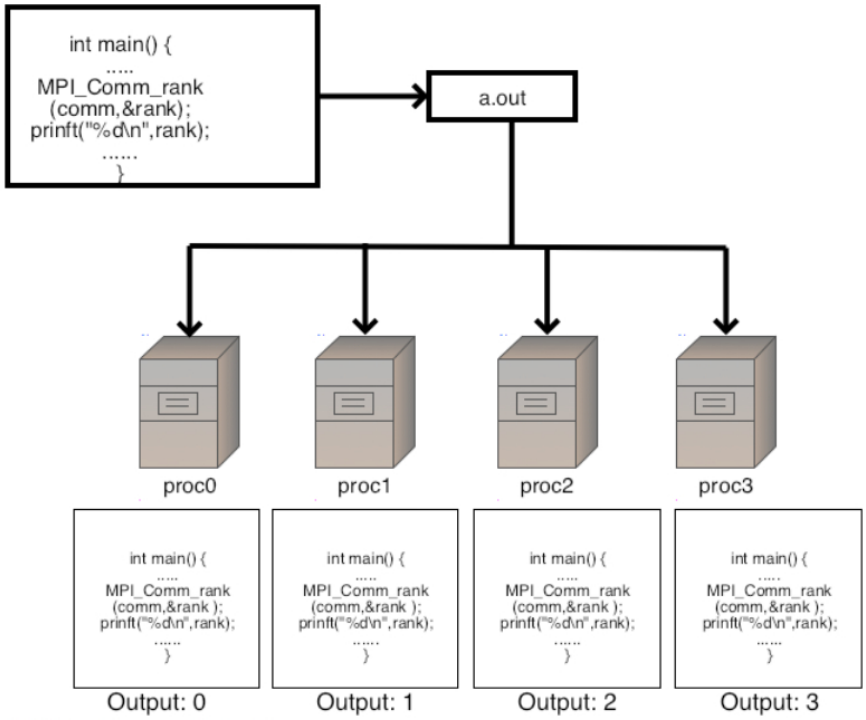


FIGURE 2.5: Parallel program that prints process rank

In other words, each process can find out `I am process 5 out of a total of 20'.

Exercise
Write a program where each process prints out a message reporting its number, and how many processes there are:

```
Hello from process 2 out of 5!
```

Write a second version of this program, where each process opens a unique file and writes to it. *On some clusters this may not be advisable if you have large numbers of processors, since it can overload the file system.*

Exercise
Write a program where only the process with number zero reports on how many processes there are in total.

In object-oriented approaches to MPI, that is, `mpi4py` and *MPL* , the *MPI_Comm_rank* and *MPI_Comm_size* routines are methods of the communicator class:

Python note
Rank and size are methods of the communicator object:

```
procid = comm.Get_rank()
nprocs = comm.Get_size()
```

The rank of a process (by `mpl::communicator::` *rank* the size of a communicator (by `mpl::communicator::` *size* are both methods of the *communicator*

```
const mpl::communicator &comm_world =
    mpl::environment::comm_world();
int procid = comm_world.rank();
int nprocs = comm_world.size();
```

2.4 Functional Parallelism

crumb trail: > mpi-functional > Functional parallelism

Now that processes can distinguish themselves from each other, they can decide to engage in different activities. In an extreme case you could have a code

that looks like

```
// climate simulation:
if (procid==0)
  earth_model();
else if (procid=1)
  sea_model();
else
  air_model();
```

Practice is a little more complicated than this. But we will start exploring this notion of processes deciding on their activity based on their process number.

Being able to tell processes apart is already enough to write some applications, without knowing any other MPI. We will look at a simple parallel search algorithm: based on its rank, a processor can find its section of a search space. For instance, in *Monte Carlo codes* a large number of random samples is generated and some computation performed on each. (This particular example requires each MPI process to run an independent random number generator, which is not entirely trivial.)

Exercise
Is the number $N = 2,000,000,111$ prime? Let each process test a disjoint set of integers, and print out any factor they find. You don't have to test all integers $< N$: any factor is at most $\sqrt{N} \approx 45,200$.

(Hint: `i%0` probably gives a runtime error.)

Can you find more than one solution?

Remark
Normally, we expect parallel algorithms to be faster than sequential. Now consider the above exercise. Suppose the number we are testing is divisible by some small prime number, but every process has a large block of numbers to test. In that case the sequential algorithm would have been faster than the parallel one. Food for thought.

As another example, in *Boolean satisfiability* problems a number of points in a search space needs to be evaluated. Knowing a process's rank is enough to let it generate its own portion of the search space. The computation of the *Mandelbrot set* can also be considered as a case of functional parallelism. However, the image that is constructed is data that needs to be kept on one processor, which breaks the symmetry of the parallel run.

Of course, at the end of a functionally parallel run you need to summarize the results, for instance printing out some total. The mechanisms for that you will learn next.

2.5 Review Questions

For all true/false questions, if you answer that a statement is false, give a one-line explanation.

Exercise
True or false: `mpicc` is a compiler.

Exercise
T/F?

1. In C, the result of `MPI_Comm_rank` is a number from zero to number-of-processes-minus-one, inclusive.
2. In Fortran, the result of `MPI_Comm_rank` is a number from one to number-of-processes, inclusive.

Exercise
What is the function of a hostfile?

\begin{pcse}

Exercise
An architecture is called `symmetric' or `uniform' if the relation between any pair of processes is essentially the same. In what way are MPI processes run on stampede symmetric; in what way not?

\end{pcse}

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