Introduction to the Message Passing Interface (MPI)

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December 2015

Outline

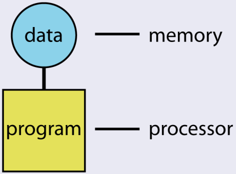
- MPI Overview
- Process model and language bindings
- Messages and point-to-point communication
- Non-blocking communication
- Derived data types
- Virtual topologies
- Collective communication

Outline

- MPI Overview
  - one program on several processors
  - work and data distribution
  - the communication network
- Process model and language bindings
- Messages and point-to-point communication
- Non-blocking communication
- Derived data types
- Virtual topologies
- Collective communication

The Message-Passing Programming Paradigm

Sequential Programming Paradigm



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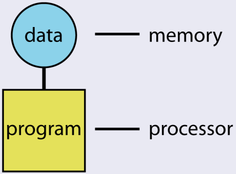
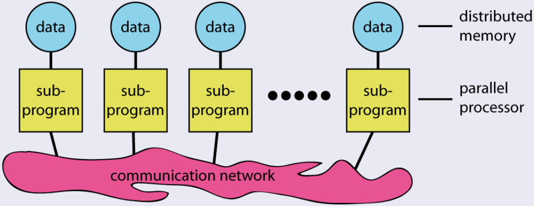


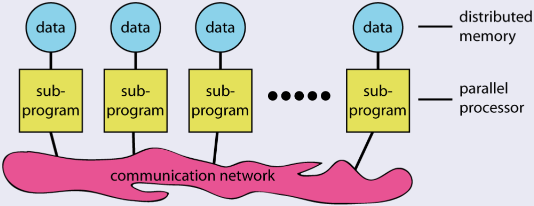
Message-Passing Programming Paradigm



The Message-Passing Programming Paradigm

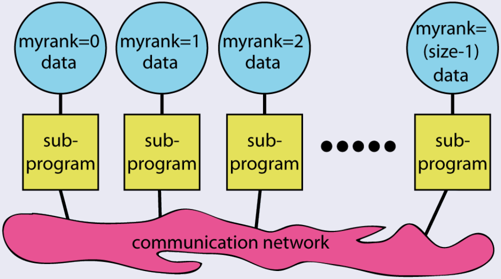
Each processor in a message passing program runs a **sub-program**

- written in a conventional sequential language, e.g., C(++) or Fortran
- typically the same on each processor (SPMD)
- the variables of each sub-program have
  - the same name
  - but different locations (distributed memory) and different data!
  - i.e., all variables are private
- communicate via special send & receive routines (**message passing**)

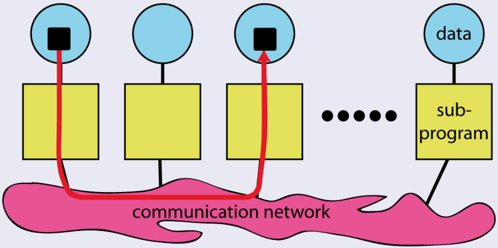


Data and Work Distribution

- the value of **myrank** is returned by special library function
- the system of **size** processes is started by special MPI initialization program (mpirun or mpiexec)
- all distribution decisions are based on **myrank**
- i.e., which process works on which data



Messages



- Messages are packets of data moving between sub-programs
- Necessary information for the message passing system:
  - sending process
  - source location
  - source data type
  - source data size
  - receiving process
  - destination location
  - destination data type
  - destination buffer size

Access

- A sub-program needs to be connected to a message passing system
- A message passing system is similar to:
  - mail box
  - phone line
  - fax machine
  - etc.
- MPI:
  - sub-program must be linked with an MPI library
  - the total program (i.e., all sub-programs of the program) must be started with the MPI startup tool

Addressing

- Messages need to have addresses to be sent to
- Addresses are similar to:
  - mail addresses
  - phone number
  - fax number
  - etc.
- MPI: addresses are ranks of the MPI processes (sub-programs)

Point-to-Point communication

- Simplest from of message passing
- One process send a message to another
- Different types of point-to-point communication:
  - non-buffered = synchronous send
  - buffered = asynchronous send

Synchronous/Asynchronous Sends

Synchronous Sends

- The sender gets an information that the message is received
- Analog to the beep or okay-sheet of a fax

Synchronous/Asynchronous Sends

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Buffered = Asynchronous Sends

- We only know when the message has left

Synchronous/Asynchronous Sends – Examples

Process 0

```
send    ( &a, 1, 1 );
receive( &b, 1, 1 );
```

Process 1

```
send    ( &a, 1, 0 );
receive( &b, 1, 0 );
```

Synchronous/Asynchronous Sends – Examples

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Depending on the implementation of `send` and `receive` this might lead to a **deadlock**!

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Synchronous/Asynchronous Sends – Examples

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receive( &b, 1, 1 );
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Process 1

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receive( &b, 1, 0 );
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```

Even with buffered send this code will lead to a **deadlock**!

Blocking Operations

- Operations are local activities, e.g.,
  - sending (a message)
  - receiving (a message)
- Some operations may **block** until another process acts:
  - synchronous send operation **blocks until** receive is posted
  - receive operation **blocks until** message is sent
- Relates to the completion of an operation
- Blocking subroutine returns only when the operation has completed

Non-Blocking Operations

- Non-blocking operation: returns immediately and allow the sub-program to perform other work.
- At some later time the sub-program must **test** or **wait** for the completion of the non-blocking operation.
- All non-blocking operations must have matching wait (or test) operations. (Some system or application resources can be freed only when the non-blocking operation is completed.)
- A non-blocking operation immediately followed by a matching wait is equivalent to a blocking operation
- Non-blocking operations are not the same as sequential subroutine calls: the operation may continue while the application executes the next statements!

Collective Communications

- Collective communication routines are higher level routines.
- Several processes are involved at a time
- May allow optimized internal implementations, e.g., tree based algorithms
- Can be built out of point-to-point communications

Collective Communications (cont'd)

Broadcast

- A one-to-many communication

Collective Communications (cont'd)

Broadcast

- A one-to-many communication

Reduction Operations

- Combine data from several processes to produce a single result

Collective Communications (cont'd)

Broadcast

- A one-to-many communication

Reduction Operations

- Combine data from several processes to produce a single result

Barriers

- Synchronize processes

Goals and Scope of MPI

- MPI's prime goals
  - to provide a message-passing interface
  - to provide source-code portability
  - to allow efficient implementations
- it also offers:
  - a great deal of functionality
  - support for heterogeneous parallel architectures
- With MPI-2:
  - important additional functionality
  - no changes to MPI-1.
- With MPI-2.1, 2.2, 3.0:
  - important additional functionality to fit on new hardware principles
  - deprecated MPI routines moved to chapter "Deprecated Functions"

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- MPI Overview
- Process model and language bindings
  - starting several MPI processes
- Messages and point-to-point communication
- Non-blocking communication
- Derived data types
- Virtual topologies
- Collective communication

Compilation/Header Files/Function Format

Compilation

```
g++ ... -L<mpi_library_path> -l<mpi_library_name>
        -I<mpi_include_path> ...
mpiCC ...
```

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```
#include <mpi.h>
```

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Header files

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#include <mpi.h>
```

MPI Function Format

```
error = MPI_Xxxxx( parameter, ... );
MPI_Xxxxxx( parameter, ... );
```

MPI Function Format Details

- `MPI_....` namespace is reserved for MPI constants and routines, i.e., application routines and variable names must not begin with `MPI_`.
- Output arguments in C(++) are handled via passing-by-pointer:

Function definitions

```
MPI_Comm_rank( ..., int *rank );
MPI_Recv( ..., MPI_Status *status );
```

Usage in your code

```
main( ... ) {
   int myrank;
   MPI_Status recv_status;
   MPI_Comm_rank( ..., &myrank );
   MPI_Recv( ..., &recv_status );
}
```

Initializing MPI

- Should be the very first function call inside the `main` function
- Must be the very first MPI function call

Function definition

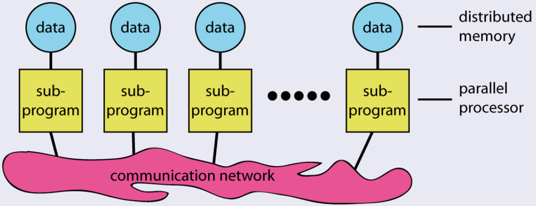
```
MPI_Init( int *argc, char ***argv );
```

Usage in your code

```
#include <mpi.h>
int main( int argc, char** argv )
{
   MPI_Init( &argc, &argv );
   ...
}
```

Starting the MPI Program

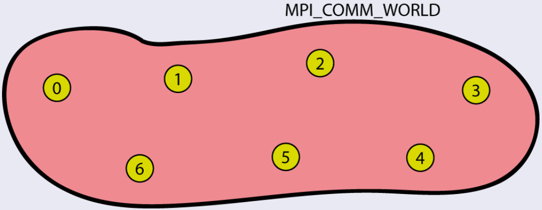
- Start mechanism is implementation dependent
- mpirun -np *number_of_processes ./executable* (most implementations)
- mpiexec -n *number_of_processes ./executable* (with MPI-2 standard)



- The parallel MPI processes exist at least after `MPI_Init` was called.

Communicator MPI_COMM_WORLD

- All processes (= sub-programs) of one MPI program are combined in the communicator `MPI_COMM_WORLD`
- `MPI_COMM_WORLD` is a predefined **handle** in `mpi.h`
- Each process has its own **rank** in a communicator:
  - starting with 0
  - ending with size-1



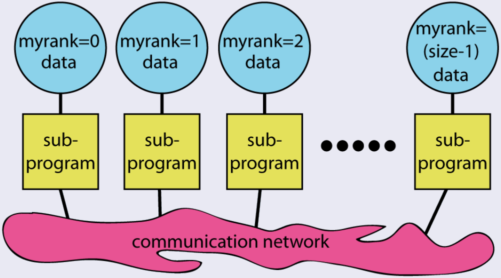
Handles

- Handles identify MPI objects
- For the programmer, handles are
  - predefined constants in `mpi.h`
    - example: `MPI_COMM_WORLD`
    - predefined values exist only after `MPI_Init` was called
  - values returned by some MPI routines, to be stored in variables that are defined as special MPI typedefs
- Handles refer to internal MPI data structures

Rank

- The rank identifies different processes
- The rank is the basis for any work and data distribution

```
int MPI_Comm_rank( MPI_Comm comm, int *rank );
```



Size

- How many processes are contained within a communicator?

```
int MPI_Comm_size( MPI_Comm comm, int *size );
```

Exiting MPI

```
int MPI_Finalize();
```

- MUST be called last by all processes
- After `MPI_Finalize`:
  - Further MPI-calls are forbidden
  - Especially re-initialization with `MPI_Init` is forbidden

Example: MPI Hello World (I)

```
#include <mpi.h>

int main( int argc, char **argv )
{
   // Definition of the variables
   int size;  //The total number of processes
   int rank;  //The rank/number of this process

   // MPI initialization
   MPI_Init( &argc, &argv );

   // Determining the number of CPUs and the rank for each CPU
   MPI_Comm_size( MPI_COMM_WORLD, &size );
   MPI_Comm_rank( MPI_COMM_WORLD, &rank );

   ...
```

Example: MPI Hello World (II)

```
   ...

   // 'Hello World' output for CPU 0
   if( rank == 0 )
      cout << " Hello World" << endl;

   // Output of the own rank and size of each CPU
   cout << " I am CPU " << rank << " of " << size << " CPUs" << endl;

   // MPI finalizations
   MPI_Finalize();

   return 0;
}
```

Example: MPI Hello World (III)

Possible output of the program:

```
I am CPU 2 of 4 CPUs
Hello World
I am CPU 0 of 4 CPUs
I am CPU 3 of 4 CPUs
I am CPU 1 of 4 CPUs
```

Note: The output of the program is non-deterministic!

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- MPI Overview
- Process model and language bindings
- Messages and point-to-point communication
  - the MPI processes can communicate
- Non-blocking communication
- Derived data types
- Virtual topologies
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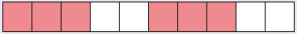
Messages

- A message contains a number of elements of some particular datatype
- MPI datatypes:
  - Basic datatype
  - Derived datatypes



- Derived datatypes can be built up from basic or derived data types
- Data type handles are used to describe the type of the data in the memory.
- Example: message with 5 integers

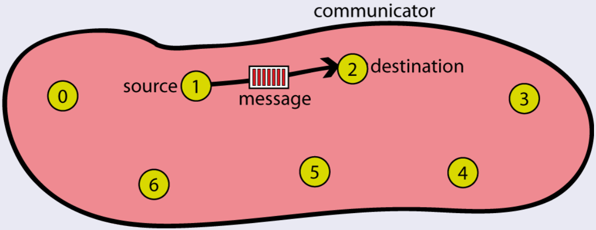
2345	654	96574	-12	7676

MPI Basic Datatypes

MPI_CHAR	char	Treated as printable character
MPI_SHORT	signed short int	
MPI_INT	signed int	
MPI_LONG	signed long int	
MPI_LONG_LONG	signed long long	
MPI_SIGNED_CHAR	signed char	Treated as integral value
MPI_UNSIGNED_CHAR	unsigned char	Treated as integral value
MPI_UNSIGNED_SHORT	unsigned short int	
MPI_UNSIGNED	unsigned int	
MPI_UNSIGNED_LONG	unsigned long int	
MPI_UNSIGNED_LONG_LONG	unsigned long long	
MPI_FLOAT	float	
MPI_DOUBLE	double	
MPI_LONG_DOUBLE	long double	
MPI_BYTE		
MPI_PACKED		

Point-to-Point Communication

- Communication between two processes
- Source process sends message to destination process
- Communication takes place within a communicator, e.g., `MPI_COMM_WORLD`
- Processes are identified by their ranks in the communicator



Sending a Message

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

- `buf` is the starting point of the message with `count` elements
- `dest` is the rank of the destination process within the communicator `comm`
- `tag` is an additional nonnegative integer piggyback information, additionally transferred with the message
- The tag can be used by the program to distinguish different types of messages

Receiving a Message

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

- `buf`, `count`, `datatype` describe the receive buffer
- Receiving the message sent by process with rank `source` in `comm`
- Envelope information is returned in `status`
- Only messages with matching `tag` are received

Requirements for Point-to-Point Communications

For a communication to succeed:

- Sender must specify a valid destination rank
- Receiver must specify a valid source rank
- The communicator must be the same
- Tags must match
- Message datatypes must match
- Receiver's buffer must be large enough

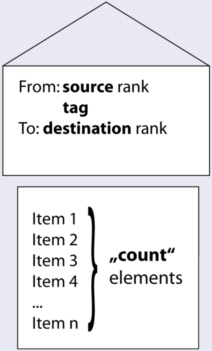
Wildcarding

- Receiver can wildcard
- To receive from any source ⇒ `source` = `MPI_ANY_SOURCE`
- To receive from any tag ⇒ `tag` = `MPI_ANY_TAG`
- Actual source and tag are returned in the receiver's `status` parameter

Communication Envelope

Envelope information is returned from `MPI_Recv` in `status`

```
status.MPI_SOURCE
status.MPI_TAG
status.MPI_ERROR
count via MPI_Get_count()
```




```
int MPI_Get_count( MPI_Status *status,
                   MPI_Datatype datatype, int *count );
```

Communication Modes

Send communication modes	⇒	
- synchronous send	⇒	MPI_Ssend
- buffered [asynchronous] send	⇒	MPI_Bsend
- standard send	⇒	MPI_Send
- ready send	⇒	MPI_Rsend
Receiving all modes	⇒	MPI_Recv

Communication Modes – Definitions

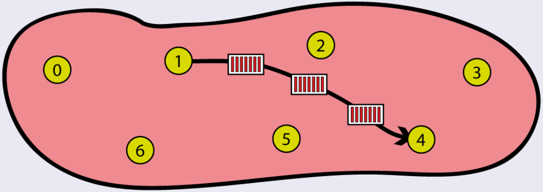
Sender mode	Definition	Notes
Synchronous send **MPI_Ssend**	Only completes when the receive has started	
Buffered send **MPI_Bsend**	Always completes (unless an error occurs), irrespective of receiver	needs application-defined buffer to be declared with MPI_Buffer_attach
Standard send **MPI_Send**	Either synchronous or buffered	Uses an internal buffer
Ready send **MPI_Rsend**	May be started **only** if the matching receive is already posted!	Highly dangerous!
Receive **MPI_Recv**	Completes when a message has arrived	same routine for all communication modes

Rules for the Communication Modes

- Standard send (**MPI_Send**)
  - minimal transfer time
  - may block due to synchronous mode
  - $\rightarrow$ risks with synchronous send
- Synchronous send (**MPI_Ssend**)
  - risk of deadlock
  - risk of serialization
  - risk of waiting $\rightarrow$ idle time
- Ready send (**MPI_Rsend**)
  - use **never**, except you have a 200% guarantee that Recv is already called in the current version and all future versions of your code

Message Order Preservation

- Rule for messages on the same connection, i.e., same communicator, source, and destination rank:
- **Messages do not overtake each other**
- This is true even for non-synchronous sends.



- If both receives match both messages, the order is preserved.

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  - - to avoid idle time and deadlocks
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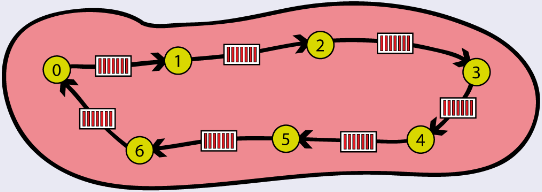
Deadlock

- Code in each MPI process:

```
// This will block and never return, because MPI_Recv
// cannot be called in the right-hand MPI process
MPI_Ssend( ..., right_rank, ... );
MPI_Recv( ..., left_rank, ... );
```



- Same problem with standard send mode (MPI_Send) if MPI implementation chooses synchronous protocol

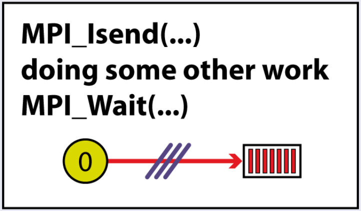
Non-Blocking Communications

Separate communication into three phases:

- Initiate non-blocking communication
  - returns immediately
  - routine name starting with `MPI_I...`
- Do some work (perhaps involving other communications?)
- Wait for non-blocking communication to complete

Non-Blocking Examples

Non-blocking send



Non-Blocking Examples

Non-blocking send

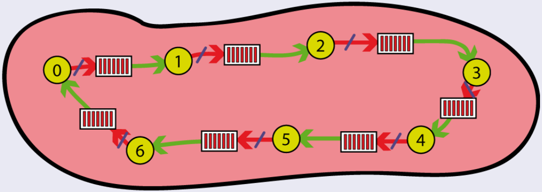
MPI_Isend(...)
doing some other work
MPI_Wait(...)

Non-blocking receive

MPI_Irecv(...)
doing some other work
MPI_Wait(...)

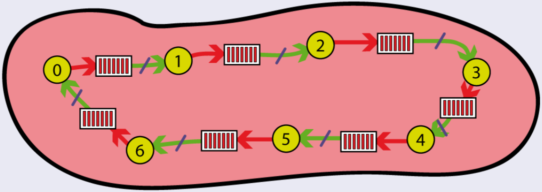
Non-Blocking Send

- Initiate non-blocking send
  $\rightarrow$ In the ring example: initiate non-blocking send to the right neighbor
- Do some work:
  $\rightarrow$ In the ring example: Receive the message from left neighbor
- Now, the message transfer can be completed
- Wait for non-blocking send to complete



Non-Blocking Receive

- Initiate non-blocking receive
  In the ring example: Initiate non-blocking receive from left neighbor
- Do some work:
  in the ring example: Sending the message to the right neighbor
- Now, the message transfer can be completed
- Wait for non-blocking receive to complete



Request Handles

Request handles

- are used for non-blocking communication
- must be stored in local variables (MPI_Request)
- the value
  - **is generated** by a non-blocking communication routine
  - **is used** (and freed) in the `MPI_Wait` routine

Non-Blocking Synchronous Send

```
int MPI_Issend( void* buf, int count,
                MPI_Datatype datatype, int dest,
                int tag, MPI_Comm comm,
                MPI_Request *request );

int MPI_Wait( MPI_Request *request, MPI_Status *status );
```

- buf must not be accessed between Issend and Wait

  (In MPI-2.2, this restriction is relaxed to "must not be modified")
- "Issend + Wait directly after Issend" is equivalent to blocking call (Ssend)
- status is not used in Issend, but in Wait (with send: nothing returned)

Non-Blocking Receive

```
int MPI_Irecv( void* buf, int count,
               MPI_Datatype datatype, int source,
               int tag, MPI_Comm comm,
               MPI_Request *request);
```

```
int MPI_Wait( MPI_Request *request, MPI_Status *status );
```

- buf must not be used between `Irecv` and `Wait`

Blocking and Non-Blocking

- Send and receive can be blocking or non-blocking
- A blocking send can be used with a non-blocking receive, and vice-versa.
- Non-blocking sends can use any mode

standard	–	MPI_Isend
synchronous	–	MPI_Issend
buffered	–	MPI_Ibsend
ready	–	MPI_Irsend

- Synchronous mode affects completion, i.e., `MPI_Wait`/`MPI_Test`, not initiation, i.e., `MPI_I...`
- The non-blocking operation immediately followed by a matching wait is equivalent to the blocking operation

Completion

```
int MPI_Wait( MPI_Request *request, MPI_Status *status );
int MPI_Test( MPI_Request *request, int *flag,
              MPI_Status *status );
```

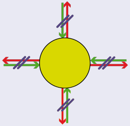
One must

- `Wait` or
- loop with `Test` until request is completed, i.e., flag == 1

Multiple Non-Blocking Communications

You have several request handles:

- Wait or test for completion of **one** message
  MPI_Waitany / MPI_Testany
- Wait or test for completion of **all** messages
  MPI_Waitall / MPI_Testall ***)**
- Wait or test for completion of **as many** messages as possible
  MPI_Waitsome / MPI_Testsome ***)**



***)** Each status contains an additional error field. This field is only used if MPI_ERR_IN_STATUS is returned (also valid for send operations)

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- Derived data types
    - - transfer of any combination of typed data
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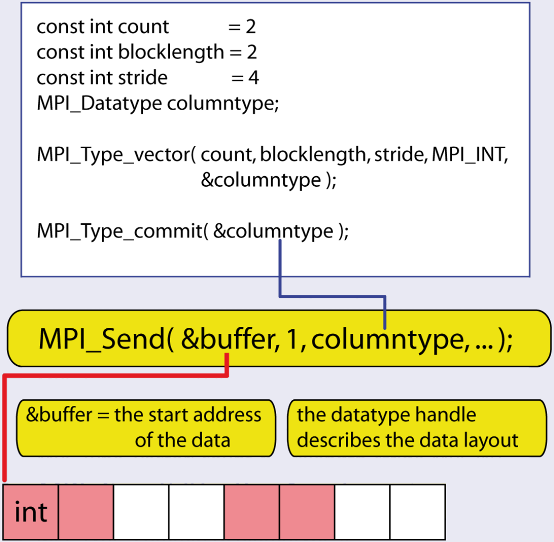
MPI Datatypes

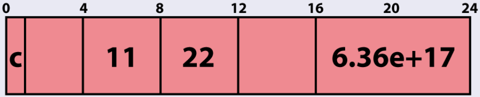
- Description of the memory layout of the buffer
  - for sending
  - for receiving
- Basic types
- Derived types
  - vectors
  - structs
  - others

Data Layout and the Describing Datatype Handle



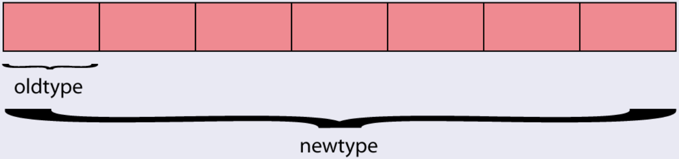
Derived Data Types – Type Maps

- A derived datatype is logically a pointer to a list of entries
- A derived datatype describes the memory layout of, e.g., structures, common blocks, subarrays, some variables in the memory
- Example:



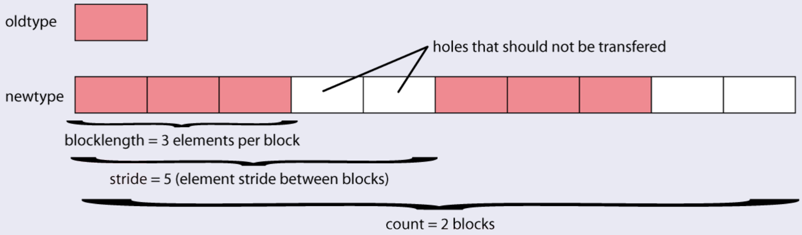
basic datatype	displacement
MPI_CHAR	0
MPI_INT	4
MPI_INT	8
MPI_DOUBLE	16

- The simplest derived datatype
- Consists of a number of contiguous items of the same datatype




```
int MPI_Type_contiguous( int count, MPI_Datatype oldtype,
                         MPI_Datatype *newtype );
```

Vector Datatype




```
int MPI_Type_vector( int count, int blocklength,
                     int stride, MPI_Datatype oldtype,
                     MPI_Datatype *newtype );
```

Committing a Datatype

- Before a datatype handle is used in message passing communication, **it needs to be committed with MPI_Type_commit**
- This must be done only once (by each MPI process)

```
int MPI_Type_commit( MPI_Datatype *datatype );
```

Size and Extent of a Datatype

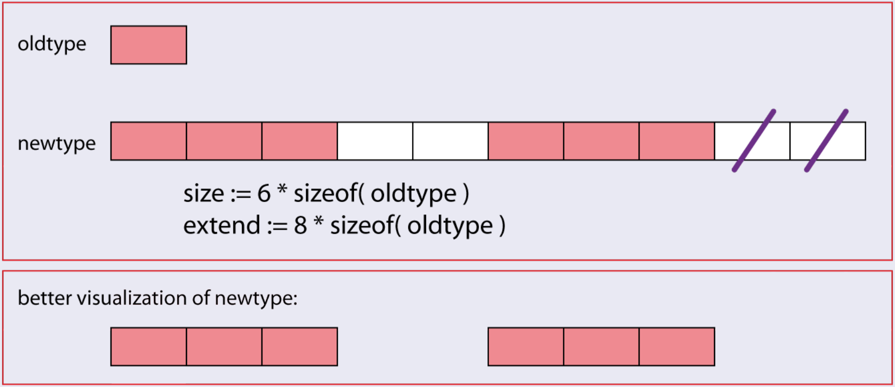
- Size := number of bytes that have to be transferred
- Extend := spans from first to last byte
- Basic datatypes: Size = Extend = number of bytes used by the compiler
- Derived datatypes:

```
int MPI_Type_size      (MPI_Datatype datatype, MPI_int *size);
int MPI_Type_get_extent(MPI_Datatype datatype, MPI_int *extent); [MPI-2]

int MPI_Type_extent(MPI_Datatype datatype, MPI_int *extent); [deprecated]
```

Size and Extent of a Datatype (cont'd)

Example 1



Outline

- MPI Overview
- Process model and language bindings
- Messages and point-to-point communication
- Non-blocking communication
- Derived data types
- Virtual topologies
  - - a multi-dimensional process naming scheme
- Collective communication

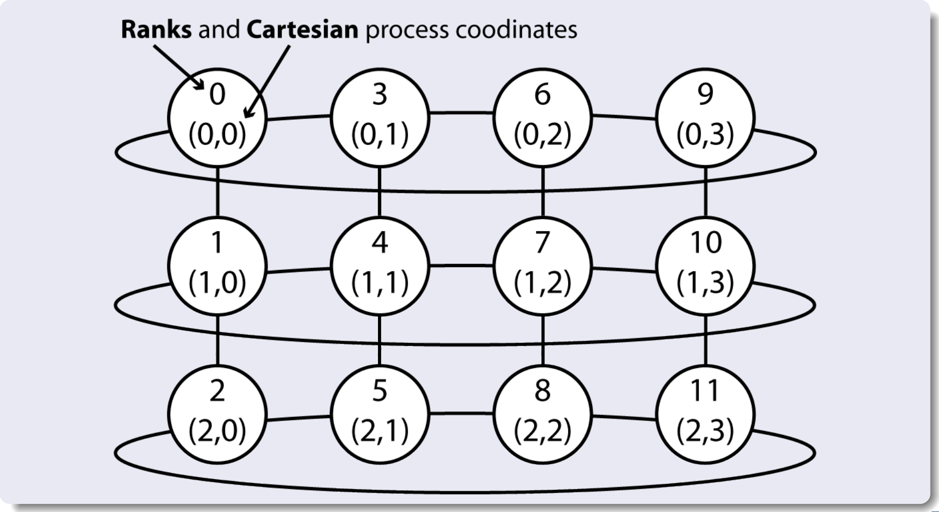
Virtual Topologies

- Convenient process naming
- Naming scheme to fit the communication pattern
- Simplifies writing of code
- Can allow MPI to optimize communications

How to use a Virtual Topology

- Creating a topology produces a new communicator
- MPI provides mapping functions
  - to compute process ranks, based on the topology naming scheme
  - and vice versa.

Example – A 2-dimensional Cylinder



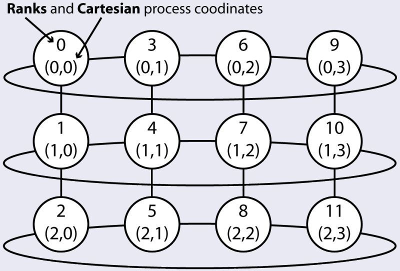
Topology Types

- Cartesian Topologies
  - each process is connected to its neighbor in a virtual grid
  - boundaries can be cyclic, or not
  - processes are identified by Cartesian coordinates
  - of course, communication between any two processes is still allowed
- Graph Topologies
  - general graphs
  - not covered here

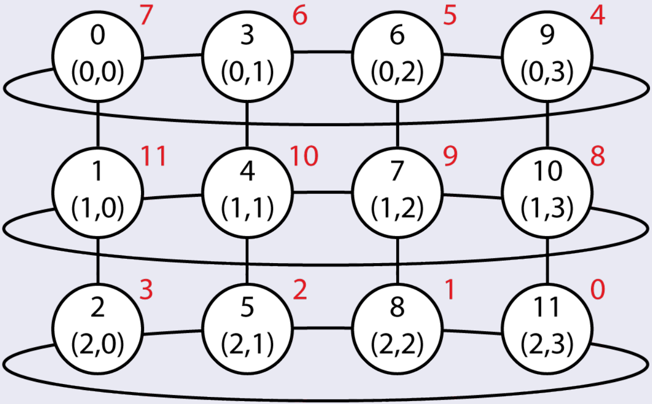
Creating a Cartesian Virtual Topology

```
int MPI_Cart_create( MPI_Comm comm_old, int ndims,
                     int *dims, int *periods, int reorder,
                     MPI_Comm *comm_cart );
```

```
comm_old = MPI_COMM_WORLD
   ndims = 2
     dim = { 3, 4 }
 periods = { 0, 1 }
 reorder = see next slide
```



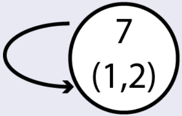
Example – A 2-dimensional Cylinder



- Ranks in `comm` and `comm_cart` may differ, if `reorder == 1`
- This reordering can allow MPI to optimize communications

Cartesian Mapping Functions

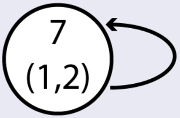
Mapping ranks to process grid coordinates




```
MPI_Cart_coords( MPI_Comm comm, int rank,
                 int maxdims, int *coords );
```

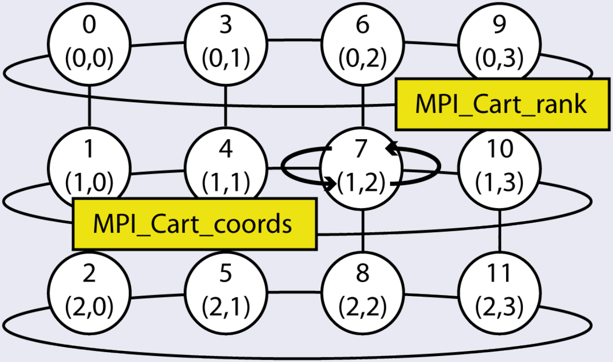
Cartesian Mapping Functions

Mapping process grid coordinates to ranks




```
MPI_Cart_rank( MPI_Comm comm, int *coords, int *rank );
```

Own Coordinates



Each process gets its own coordinates with

```
MPI_Comm_rank  ( comm_cart, &my_rank );
MPI_Cart_coords( comm_cart, my_rank, maxdims, my_coords );
```

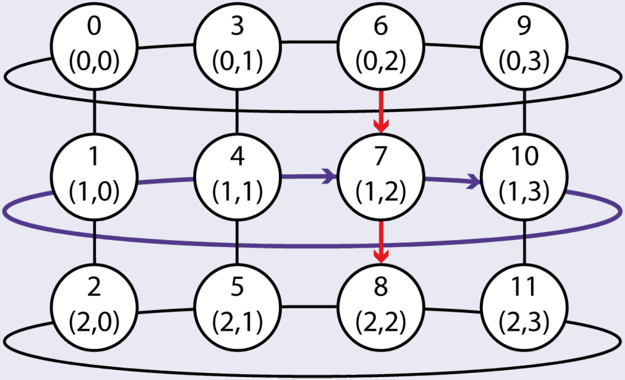
Cartesian Mapping Functions

- Computing ranks of neighboring processes

```
MPI_Cart_shift( MPI_Comm comm, int direction, int disp,
                int *rank_source, int *rank_dest );
```

- Returns MPI_PROC_NULL if there is no neighbor
- MPI_PROC_NULL can be used as source or destination rank in each communication → Then, this communication will be a noop!

MPI_Cart_shift – Example




```
MPI_Cart_shift( cart, direction, displace, rank_source, rank_dest );
```

	direction	displace	rank_source	rank_dest
example of	0	+1	6	8
process rank=7	1	+1	4	10

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- MPI Overview
- Process model and language bindings
- Messages and point-to-point communication
- Non-blocking communication
- Derived data types
- Virtual topologies
- Collective communication
    - - e.g., broadcast

Collective communication

- Communications involving a group of processes
- Called by all processes in a communicator
- Examples:
  - Barrier synchronization
  - Broadcast, scatter, gather
  - Global sum, global maximum, etc.

Characteristics of Collective communication

- Collective action over a communicator
- All processes of the communicator must communicate, i.e., must call the collective routine
- Synchronization may or may not occur, therefore all processes must be able to start the collective routine
- All collective operations are blocking
- No tags
- Receive buffers must have exactly the same size as send buffers

Barrier Synchronization

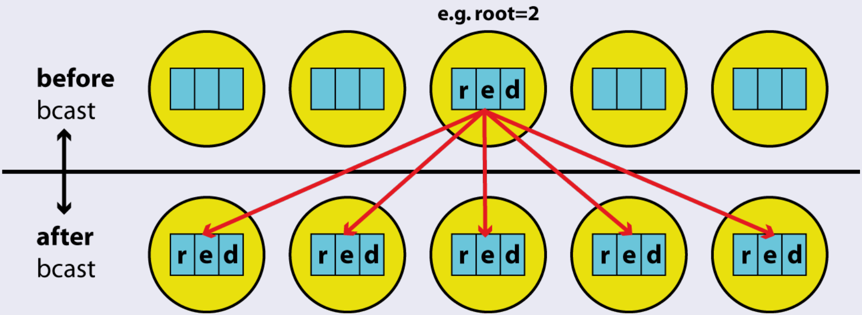
```
MPI_Barrier( MPI_Comm comm );
```

`MPI_Barrier` is normally never needed:

- all synchronization is done automatically by the data communication
  - a process cannot continue before it has the data that it needs
- if used for debugging
  - please guarantee, that it is removed in production
- for profiling: to separate time measurement of
  - Load imbalance of computation [MPI_Wtime(); MPI_Barrier(); MPI_Wtime();]
  - communication epochs [MPI_Wtime(); MPI_Allreduce(); ...; MPI_Wtime()]
- if used for synchronizing external communication (e.g., I/O)
  - exchanging tokens may be more efficient and scalable than a barrier on `MPI_COMM_WORLD`

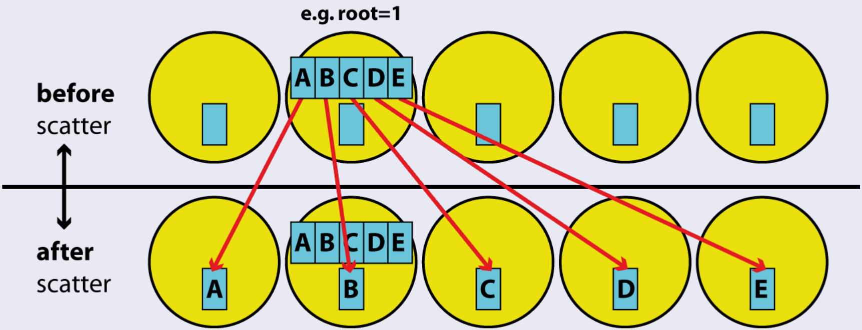
Broadcast

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



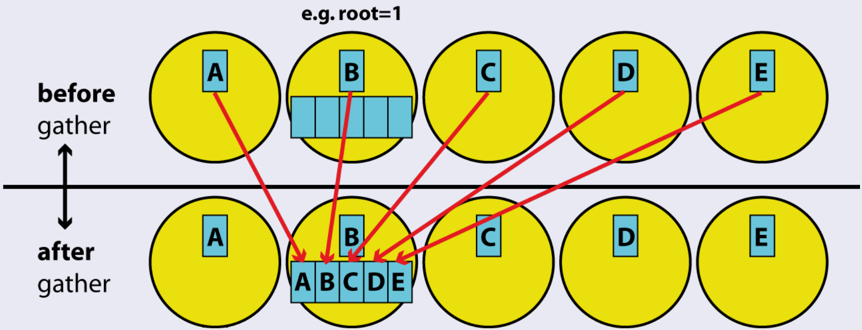
Scatter

```
int MPI_Scatter( void* sendbuf, int sendcount,
                 MPI_Datatype sendtype, void* recvbuf,
                 int recvcount, MPI_Datatype recvtype,
                 int root, MPI_Comm comm );
```



Gather

```
int MPI_Gather( void* sendbuf, int sendcount,
                MPI_Datatype sendtype, void* recvbuf,
                int recvcount, MPI_Datatype recvtype,
                int root, MPI_Comm comm );
```



Global Reduction Operations

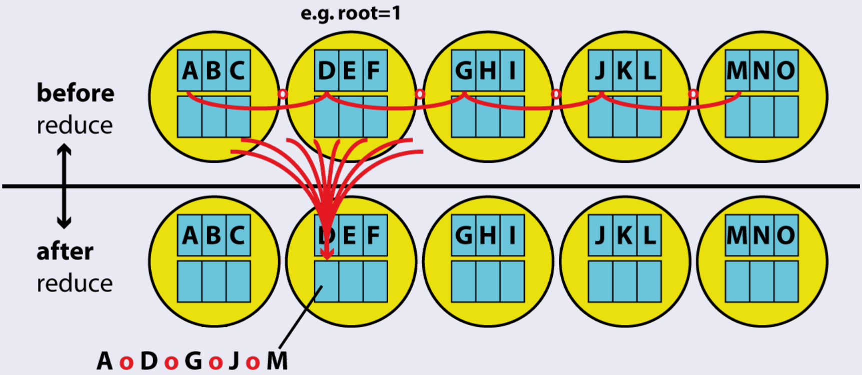
- To perform a global reduce operation across all members of a group
- $d_0 \circ d_1 \circ d_2 \circ \ldots \circ d_{s-2} \circ d_{s-1}$
  - d_i = data in process rank i
    - single variable, or
    - vector
  - $\circ$ = associative operation
  - Example:
    - global sum or product
    - global maximum or minimum
    - global user-defined operation
  - floating point rounding may depend on usage of associative law
    - $[(d_0 \circ d_1) \circ (d_2 \circ d_3)] \circ [\ldots \circ (d_{s-2} \circ d_{s-1})]$
    - $((((((d_0 \circ d_1) \circ d_2) \circ d_3) \circ \ldots) \circ d_{s-2}) \circ d_{s-1})$

Predefined Reduction Operation Handles

Predefined operation handle	Function
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical AND
MPI_BAND	Bitwise AND
MPI_LOR	Logical OR
MPI_BOR	Bitwise OR
MPI_LXOR	Logical exclusive OR
MPI_BXOR	Bitwise exclusive OR
MPI_MAXLOC	Maximum and location of the maximum
MPI_MINLOC	Minimum and location of the minimum

MPI_Reduce

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



Example of Global Reduction

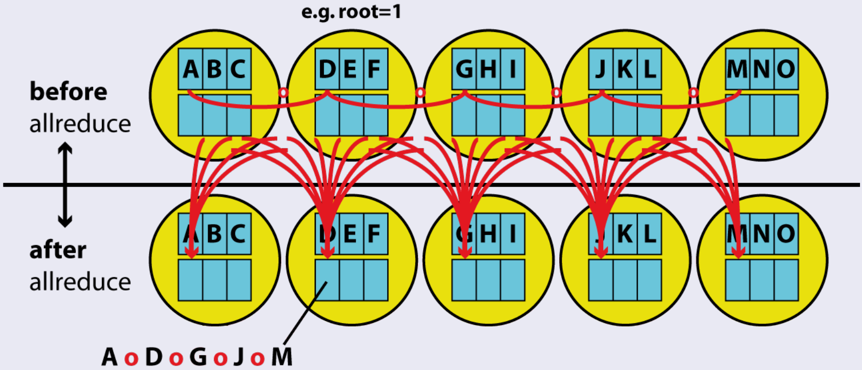
- Global integer sum
- Sum of all inbuf values should be returned in `resultbuf`
- ```
  root = 0;
  MPI_reduce( &inbuf, &resultbuf, 1, MPI_INT, MPI_SUM,
              root, MPI_COMM_WORLD );
  ```
- The result is only placed in `resultbuf` at the root process
  ```

Variants of Reduction Operations

- MPI_Allreduce
  - no root
  - returns the result in all processes
- MPI_Reduce_scatter
  - result vector of the reduction operation is scattered to the processes into the real result buffers
- MPI_Scan
  - prefix reduction
  - result at process with rank i := reduction of inbuf-values from rank 0 to rank i

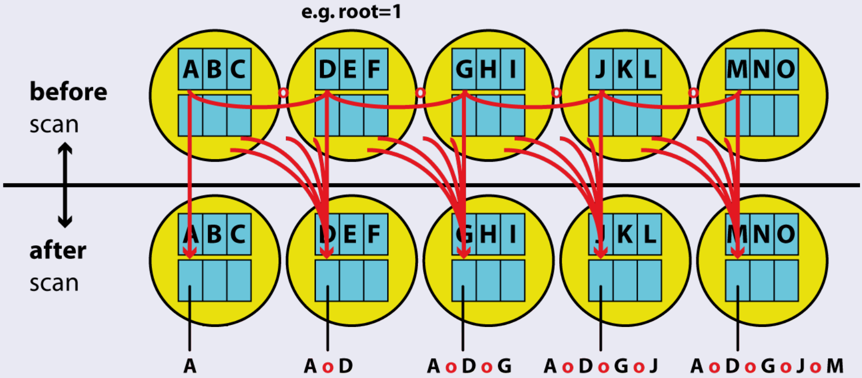
MPI_Allreduce

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



MPI_Scan

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



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- MPI Overview
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- Serialization
    - - how to order the execution of MPI processes

Motivation

Question

How can MPI processes be serialized?

Solution 1

```
if( rank == 0 ) /* ... */
MPI_Barrier( MPI_COMM_WORLD );
if( rank == 1 ) /* ... */
MPI_Barrier( MPI_COMM_WORLD );
// ...
```

Solution 1

```
if( rank == 0 ) /* ... */
MPI_Barrier( MPI_COMM_WORLD );
if( rank == 1 ) /* ... */
MPI_Barrier( MPI_COMM_WORLD );
// ...
```

```
MPI_Comm_size( MPI_COMM_WORLD, &size );
MPI_Comm_rank( MPI_COMM_WORLD, &rank );

for( int i=0; i<size; ++i ) {
   if( i == rank ) /* ... */
   MPI_Barrier( MPI_COMM_WORLD );
}
```

Solution 2

- Each process waits for a message from the processes with `rank-1` (blocking receive)
- Do some work
- Send a message to the process with rank `rank+1`