Parallel programming

MPI basics

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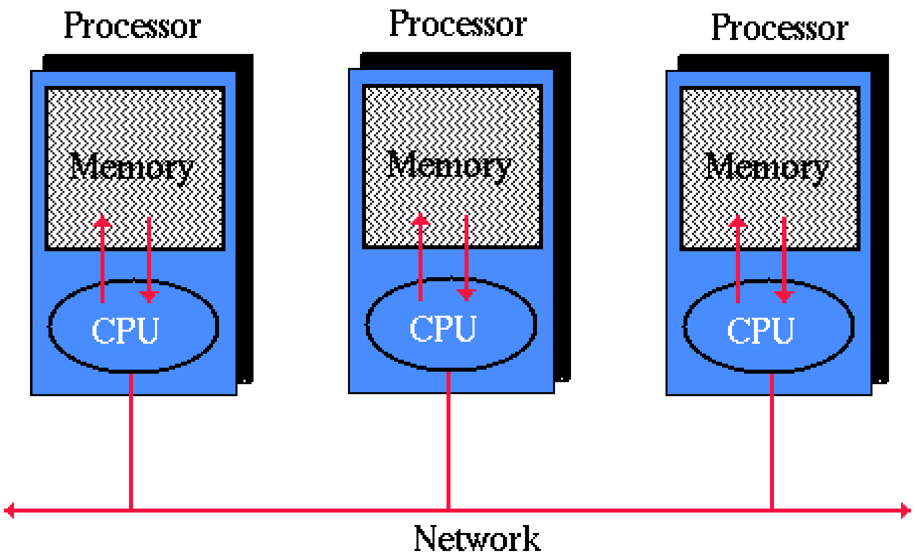
Distributed memory

- **Node independence**: each computing node operates independently, with its own local memory
- **Communication challenges**: explicit communication mechanisms to exchange data
- **Scalability**: distribute workloads and manage resources



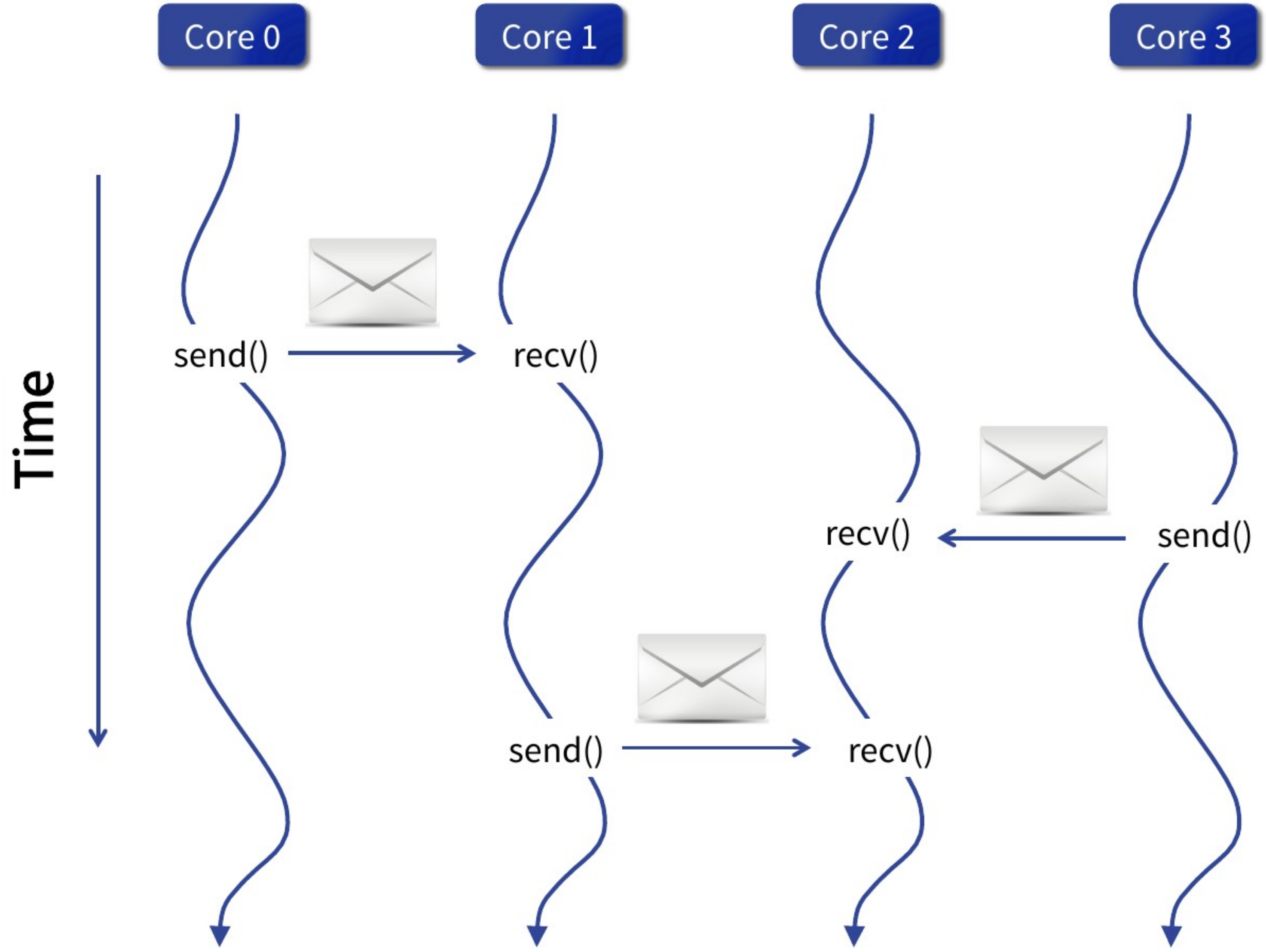
Distributed memory

- Each unit has its **own memory space**
- **Explicit communication** between units (often through a network) is required
  - point-to-point communication
  - collective communication
- Frequent application: *cluster computing*

MPI: Message Passing Interface

- A **standard** for developing parallel distributed applications
- MPI is supported by many programming languages and platforms:
  - *C, C++, and Fortran*
  - For JAVA see: *Message Passing for Java Express (MPJ Express)*
  - For .NET see: *https://github.com/mpidotnet/MPI.NET*

Communication example



MPI: Message Passing Interface

- All processes run the **same program**
- Each process is assigned a **rank**
  (i.e., identification of the process)
- Processes with different ranks can differ in what they execute
- Processes communicate by **sending and receiving** messages through a **communicator**

Example: “Hello, world!”

- Use `HelloWorld.cpp` skeleton
- Write a program that
  - Initializes MPI
  - Each process prints its rank
  - Process with rank 0 prints the total number of processes (communicator size)

Basic MPI operations

- **`#include <mpi.h>`**
  - Include the header file with MPI functions
- **`int MPI_Init(int *argc, char ***argv)`**
  - Initializes MPI runtime environment
- **`int MPI_Finalize()`**
  - Terminates MPI execution environment
- **`int MPI_Comm_size(MPI_Comm comm, int *size)`**
  - Queries the *size* of the group associated with the communicator
  - `MPI_COMM_WORLD`: default communicator grouping all the processes
- **`int MPI_Comm_rank(MPI_Comm comm, int *rank)`**
  - Queries the *rank* (identifier) of the process in the communicator

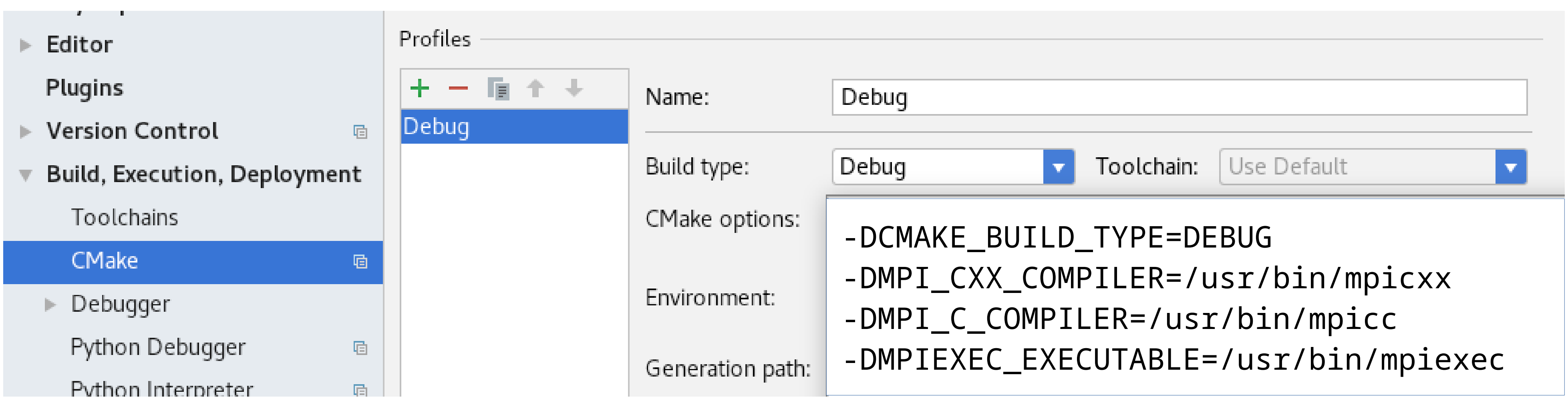
Compilation - CMake

```
cmake_minimum_required(VERSION 3.5)
project(MyProject)

find_package(MPI)
include_directories(${MPI_INCLUDE_PATH})

add_executable(Program Program.cpp)
target_compile_options(Program PRIVATE ${MPI_CXX_COMPILE_FLAGS})
target_link_libraries(Program ${MPI_CXX_LIBRARIES} ${MPI_CXX_LINK_FLAGS})
```

- CLion setup (use **whereis** command to locate paths in your operating system)



Running MPI programs

- **`mpiexec -np 4 -f hostfile PROGRAM ARGS`**
  - **np** – number of used processes
  - **`hostfile`** – file with a list of hosts on which to launch MPI processes (for cluster computing)
  - **`PROGRAM`** – program to run
  - **`ARGS`** – arguments for the program
- This will run **`PROGRAM`** using 4 processes of the cluster
- All nodes run the same program

MinGW setup:

- To be able to reach and run **mpiexec** program from the Windows Command Prompt (PowerShell), it is necessary to install a library from this link

Send a message

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

Blocking variant. For the non-blocking version, wait for a future lab.

- ***buf*** - buffer that contains the data elements to be sent
- ***count*** - number of elements to be sent
- ***datatype*** - data type of elements
- ***dest*** - rank of the target process
- ***tag*** - message tag which can be used by the receiver to distinguish between different messages from the same sender
- ***comm*** - communicator used for the communication


  ```

Receive a message

- ```
  int MPI_Recv(void *buf,
               int count,
               MPI_Datatype datatype,
               int source,
               int tag,
               MPI_Comm comm,
               MPI_Status *status)
  ```
- Same as before. New arguments:
  - ***count*** – maximal number of elements to be received
  - ***source*** – rank of the source process
  - ***status***
    - data structure that contains information (rank of the sender, tag of the message, actual number of received elements) about the message that was received
    - can be used by functions such as **MPI_Get_count** (returns the number of elements in the message)
    - If not needed, **MPI_STATUS_IGNORE** can be used instead
- Each **MPI_Send** must be matched with a corresponding **MPI_Recv**
- Messages are delivered in the order in which they have been sent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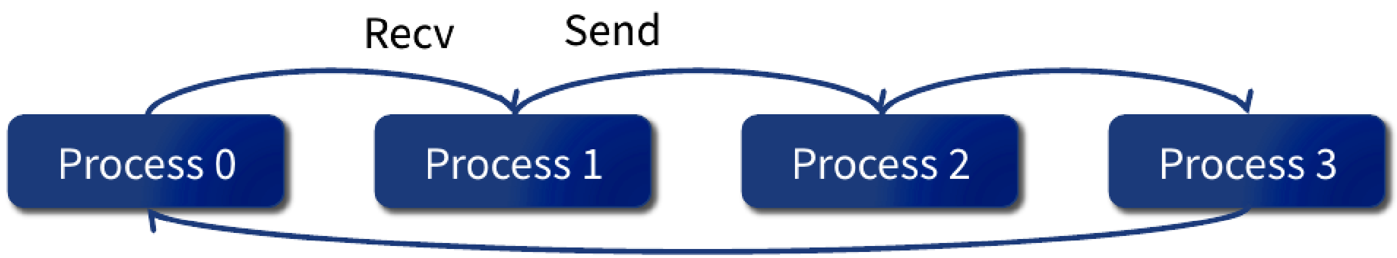
Datatypes in MPI

MPI data type	C data type
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_LONG_LONG_INT	long long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_UNSIGNED_LONG_LONG	unsigned long long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_WCHAR	wide char
MPI_PACKED	special data type for packing
MPI_BYTE	single byte value

Simultaneous Send and Receive

- ```
  int MPI_Sendrecv(const void *sendbuf,
                   int sendcount,
                   MPI_Datatype sendtype,
                   int dest,
                   int sendtag,
                   void *recvbuf,
                   int recvcount,
                   MPI_Datatype recvtype,
                   int source,
                   int recvtag,
                   MPI_Comm comm,
                   MPI_Status *status)
  ```
- Parameters: Combination of parameters for **Send** and **Receive**
- Performs send and receive at the same time
- Useful for data exchange and ring communication: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Example: “Send me a secret code!”

- Use `SendAndReceive.cpp` skeleton
- Write a program that
  - sends short message “IDDQD” from one process to another one
  - receiving process prints the result

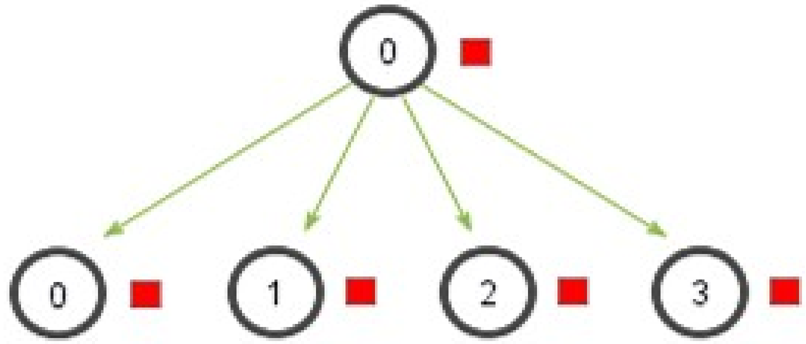
```
 _______
< IDDQD >
 -------
        \   ^__^
         \  (oo)\_______
            (__)\       )\/\
                ||----w |
                ||     ||
```

Collective communication

- Communication between **all** the processes **inside a communicator group**
- Examples of collective communication:
  - spread common data to all processes
  - gather results from many processes
  - etc.
- MPI provides several functions implementing collective communication patterns
- All these operations have:
  - A blocking version
  - A non-blocking version

Broadcast message

- ```
  int MPI_Bcast(void *buf,
                int count,
                MPI_Datatype datatype,
                int root,
                MPI_Comm comm)
  ```
- The simplest communication: one process sends a piece of data to all other processes
- Parameters:
  - ***root*** – rank of the process that provides data (all others receive it)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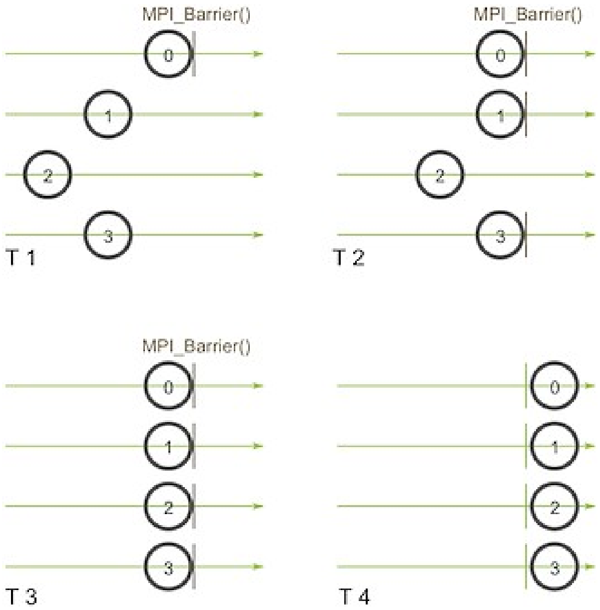
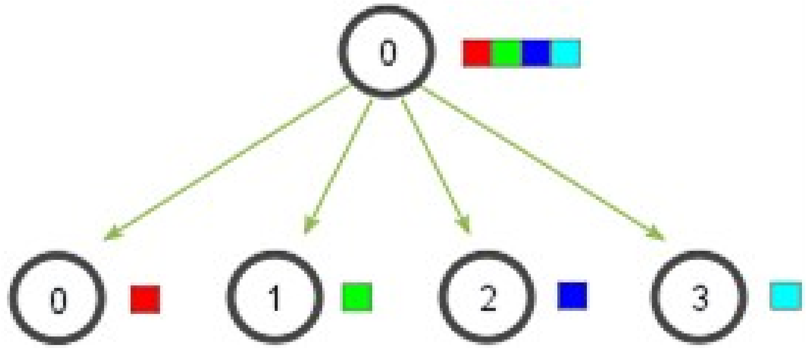
Barrier synchronization

- **`int MPI_Barrier(MPI_Comm *comm*)`**
- Synchronization point among processes.
  - All **processes must reach a point** in their code before they can all begin executing again



Scatter operation

- ```
  int MPI_Scatter(const void *sendbuf,
                  int sendcount,
                  MPI_Datatype sendtype,
                  void *recvbuf,
                  int recvcount,
                  MPI_Datatype recvtype,
                  int root,
                  MPI_Comm comm)
  ```
- Sends personalized data from one root process to all other processes in a communicator group
- The primary difference between **`MPI_Bcast`** and **`MPI_Scatter`** is that MPI_Bcast sends **the same piece** of data to all processes while **`MPI_Scatter`** sends **chunks of an array** to different processes
- Parameters:
  - **`sendcount`** - dictates how many elements of a **`sendtype`** will be sent to **each** process.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Gather operation

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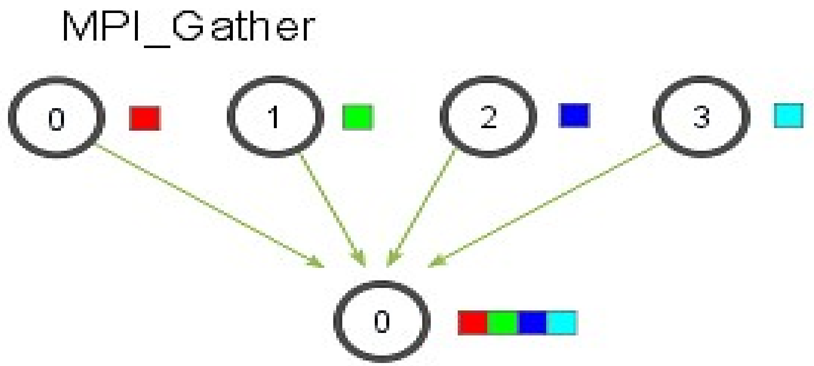
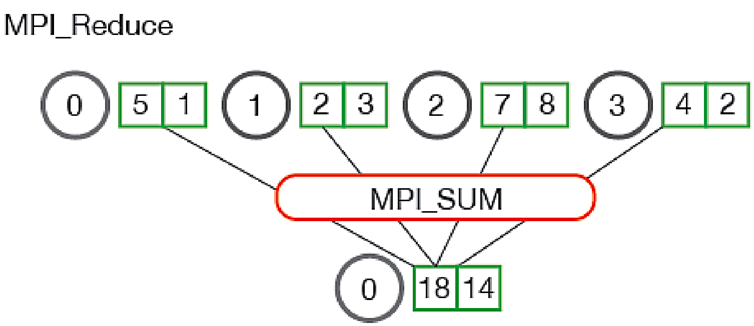
  int MPI_Gather(const void *sendbuf,
                 int sendcount,
                 MPI_Datatype sendtype,
                 void *recvbuf,
                 int recvcount,
                 MPI_Datatype recvtype,
                 int root,
                 MPI_Comm comm)
  ```

- **`MPI_Gather`** is the inverse of **`MPI_Scatter`**

- **`MPI_Gather`** takes elements from many processes and gathers them to one single root process (ordered by rank)


  ```

Reduce operation

- ```
  int MPI_Reduce(const void *sendbuf,
                 void *recvbuf,
                 int count,
                 MPI_Datatype datatype,
                 MPI_Op op,
                 int root,
                 MPI_Comm comm)
  ```
- Takes an array of input elements on each process and returns an array of output elements to the root process (similarly to Gather)
- The output elements contain the reduced result.

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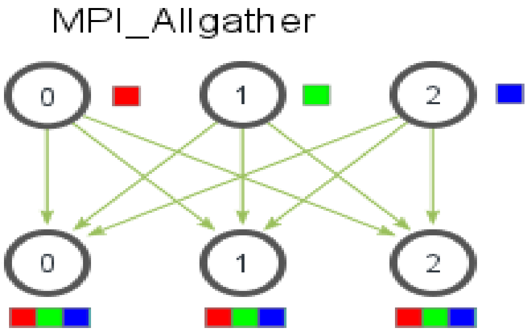
Operations for reduction

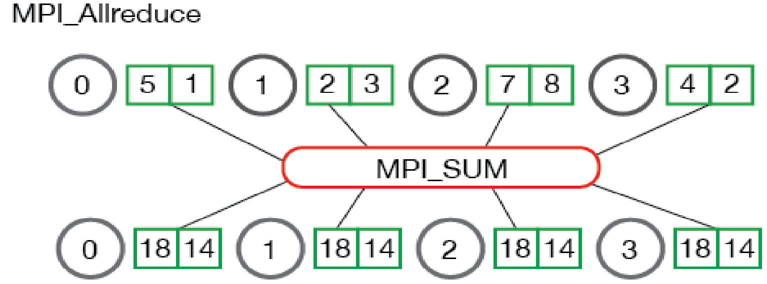
Representation	Operation
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical and
MPI_BAND	Bit-wise and
MPI_LOR	Logical or
MPI_BOR	Bit-wise or
MPI_LXOR	Logical exclusive or
MPI_BXOR	Bit-wise exclusive or
MPI_MAXLOC	Maximum value and corresponding index
MPI_MINLOC	Minimum value and corresponding index

All-versions of operations

- Works exactly like the basic operation followed by broadcasting (everyone has the same result at the end)
- **Allgather**
  - `int MPI_Allgather(const void *sendbuf, int sendcount, MPI_Datatype sendtype, void *recvbuf, int recvcount, MPI_Datatype recvtype, MPI_Comm comm)`

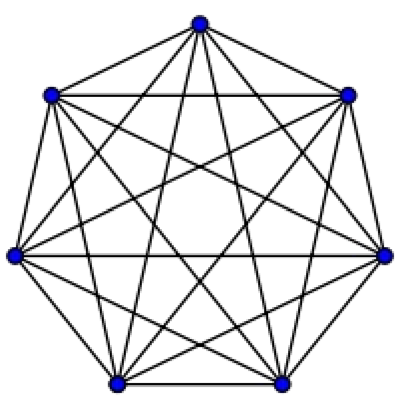


- **Allreduce**
  - `int MPI_Allreduce(const void *sendbuf, void *recvbuf, int count, MPI_Datatype datatype, MPI_Op op, MPI_Comm comm)`



All-to-All communication - Gossiping

- ```
  int MPI_Alltoall(const void *sendbuf,
                   int sendcount,
                   MPI_Datatype sendtype,
                   void *recvbuf,
                   int recvcount,
                   MPI_Datatype recvtype,
                   MPI_Comm comm)
  ```
- Each process sends personalized data to all other processes
- Total exchange of information

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Example: Vector normalization

- Use `VectorNormalization.cpp` skeleton
- Compute vector normalization using MPI:
  - Root process generates random vector, splits it into chunks and distributes the corresponding chunks to processes
  - Each process works with its chunk
  - The normalized vector is gathered in the root process

Visualization of Example 2