COMP 322: Fundamentals of Parallel Programming

Lecture 29: Introduction to the Message Passing Interface (MPI) cont.

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Worksheet #28 solution: MPI send and receive

```
1. int a[], b[];
2. ...
3. if (MPI.COMM_WORLD.rank() == 0) {
4.     MPI.COMM_WORLD.Send(a, 0, 10, MPI.INT, 1, 1);
5.     MPI.COMM_WORLD.Send(b, 0, 10, MPI.INT, 1, 2);
6. }
7. else {
8.     Status s2 = MPI.COMM_WORLD.Recv(b, 0, 10, MPI.INT, 0, 2);
9.     Status s1 = MPI.COMM_WORLD.Recv(a, 0, 10, MPI_INT, 0, 1);
10.    System.out.println("a = " + a + " ; b = " + b);
11.}
12. ...
```

Question: In the space below, indicate what values you expect the print statement in line 10 to output (assuming the program is invoked with 2 processes).

Answer: Nothing! The program will deadlock due to mismatched tags, with process 0 blocked at line 4, and process 1 blocked at line 8.

mpiJava vs. OpenMPI Java API

- mpiJava is a standalone and prototype Java library developed 10+ years ago as part of the HPJava project at Indiana University
- OpenMPI is a large consortium of universities/companies building an open-source implementation of the MPI programming model
  - Recently added Java APIs, similar to mpiJava (but more modern)
  - We will use mpiJava in lecture slides, but OpenMPI for Lab 11 and Homework 5

	mpiJava	OpenMPI Java API
Package name	package mpi	package mpi
Main class	mpi.MPI	mpi.MPI
Get MPI Rank	MPI.COMM_WORLD.Rank()	MPI.COMM_WORLD.getRank()
Get # MPI Ranks	MPI.COMM_WORLD.Size()	MPI.COMM_WORLD.getSize()
Send MPI Msg	MPI.COMM_WORLD.Send(…)	MPI.COMM_WORLD.send(…)
Recv MPI Msg	MPI.COMM_WORLD.Recv(…)	MPI.COMM_WORLD.recv(…)

Outline of today's lecture

- Blocking communications (contd)
- Non-blocking communications
- Collective communications

Basic Datatypes

- mpiJava defines 9 basic datatypes: these correspond to the 8 primitive types in the Java language, plus the MPI.OBJECT datatype that stands for an Object (or, more formally, a Java reference type).
  - MPI.OBJECT value can only be dereferenced on process where it was created
- The basic datatypes are available as static fields of the MPI class. They are:

mpiJava datatype	Java type
MPI.BYTE	byte
MPI.CHAR	char
MPI.SHORT	short
MPI.BOOLEAN	boolean
MPI.INT	int
MPI.LONG	long
MPI.FLOAT	float
MPI.DOUBLE	double
MPI.OBJECT	Object

Communication Buffers

Most of the communication operations take a sequence of parameters like

Object buf, int offset, int count, Datatype type

In the actual arguments passed to these methods, buf must be an array (or a run-time exception will occur).

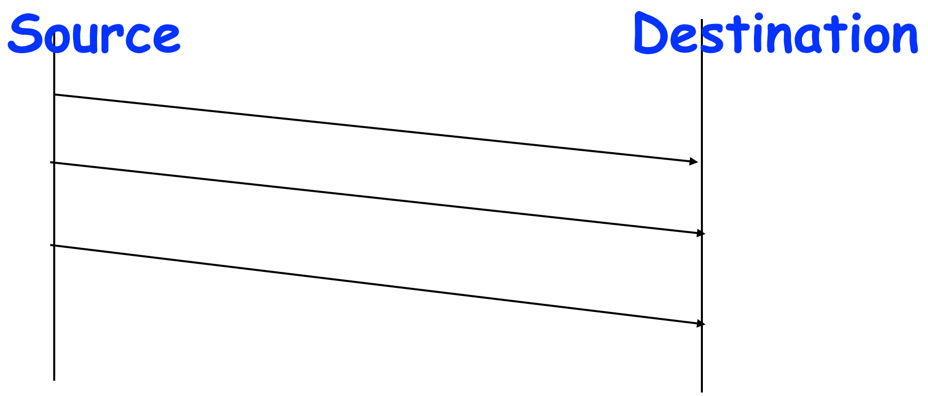
Would need to override with 8 versions of methods using 1 buffer

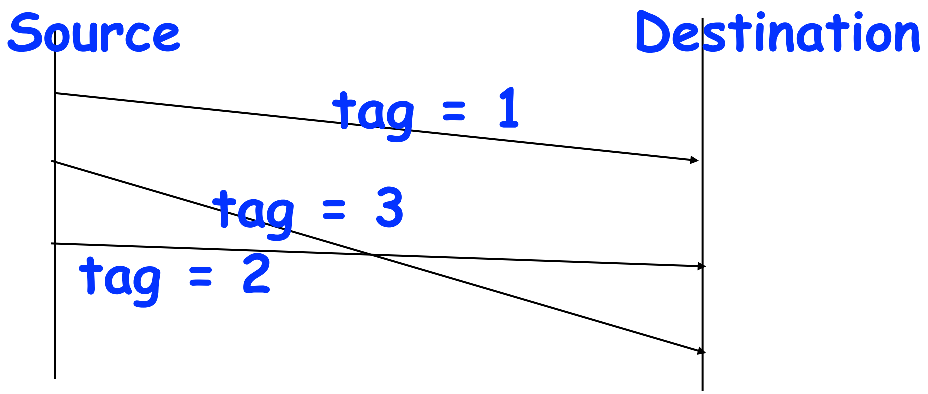
void Send(int[] buf, …)
void Send(long[] buf, …)

Would need to override with 64 versions of methods using 2 buffers

void Reduce(int[] sbuf, …int[] rbuf)
void Reduce(int[] sbuf, …long[] rbuf)

Message Ordering in MPI



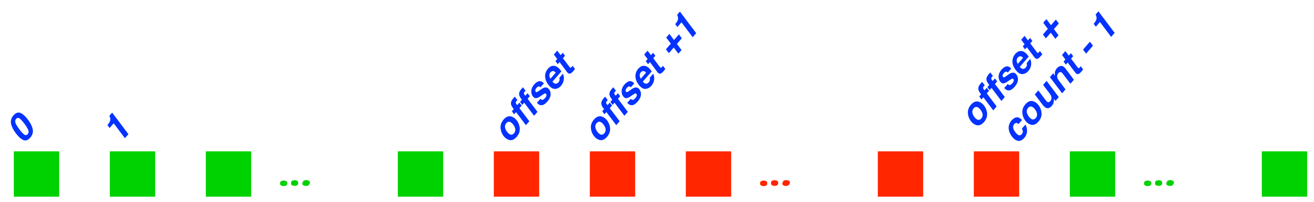


- FIFO ordering only guaranteed for same source, destination, data type, and tag

- In HJ actors, FIFO ordering was guaranteed for same source and destination
  - Actor send is also "one-sided" and "non-blocking" (unlike send/ recv in MPI)

Layout of Buffer

- If type is a basic datatype (corresponding to a Java type), the message corresponds to a subset of the array buf, defined as follows:



  – In the case of a send buffer, the red boxes represent elements of the buf array that are actually sent.

  – In the case of a receive buffer, the red boxes represent elements where the incoming data may be written.

Scenario #1

Consider:

```
int a[], b[];
...
if (MPI.COMM_WORLD.rank() == 0) {
    MPI.COMM_WORLD.Send(a, 0, 10, MPI.INT, 1, 1);
    MPI.COMM_WORLD.Send(b, 0, 10, MPI.INT, 1, 2);
}
else {
    Status s2 = MPI.COMM_WORLD.Recv(b, 0, 10, MPI.INT, 0, 2);
    Status s1 = MPI.COMM_WORLD.Recv(a, 0, 10, MPI_INT, 0, 1);
}
...
```

Blocking semantics for Send() and Recv() can lead to a deadlock.

Approach #1 to Deadlock Avoidance --- Reorder Send and Recv calls

We can break the circular wait in the worksheet by reordering Recv() calls to avoid deadlocks as follows:

```
int a[], b[];
...
if (MPI.COMM_WORLD.rank() == 0) {
    MPI.COMM_WORLD.Send(a, 0, 10, MPI.INT, 1, 1);
    MPI.COMM_WORLD.Send(b, 0, 10, MPI.INT, 1, 2);
}
else {
    Status s1 = MPI.COMM_WORLD.Recv(a, 0, 10, MPI_INT, 0, 1);
    Status s2 = MPI.COMM_WORLD.Recv(b, 0, 10, MPI.INT, 0, 2);
}
...
```

Scenario #2

Consider the following piece of code, in which process i sends a message to process *i* + 1 (modulo the number of processes) and receives a message from process *i* - 1 (modulo the number of processes)

```
int a[], b[];
. . .
int npes = MPI.COMM_WORLD.size();
int myrank = MPI.COMM_WORLD.rank()
MPI.COMM_WORLD.Send(a, 0, 10, MPI.INT, (myrank+1)%npes, 1);
MPI.COMM_WORLD.Recv(b, 0, 10, MPI.INT, (myrank+npes-1)%npes, 1);
```

Question: does this MPI code deadlock?

Approach #2 to Deadlock Avoidance --- a combined Sendrecv() call

- Since it is fairly common to want to simultaneously send one message while receiving another.
- In mpiJava, the Sendrecv() method has the following signature:

```
Status Sendrecv(Object sendBuf, int sendOffset, int sendCount,
                Datatype sendType, int dst, int sendTag,
                Object recvBuf, int recvOffset, int recvCount,
                Datatype recvType, int src, int recvTag) ;
```

More efficient than separate sends and receives

Can avoid deadlock

— There is also a variant called Sendrecv_replace() which only specifies a single buffer

Using Sendrecv for Deadlock Avoidance in Scenario #2

Consider the following piece of code, in which process i sends a message to process *i* + 1 (modulo the number of processes) and receives a message from process *i* - 1 (modulo the number of processes)

```
int a[], b[];
. . .
int npes = MPI.COMM_WORLD.size();
int myrank = MPI.COMM_WORLD.rank()
MPI.COMM_WORLD.Sendrecv(a, 0, 10, MPI.INT, (myrank+1)%npes, 1,
                        b, 0, 10, MPI.INT, (myrank+npes-1)%npes, 1);

...
```

A combined Sendrecv() call avoids deadlock in this case

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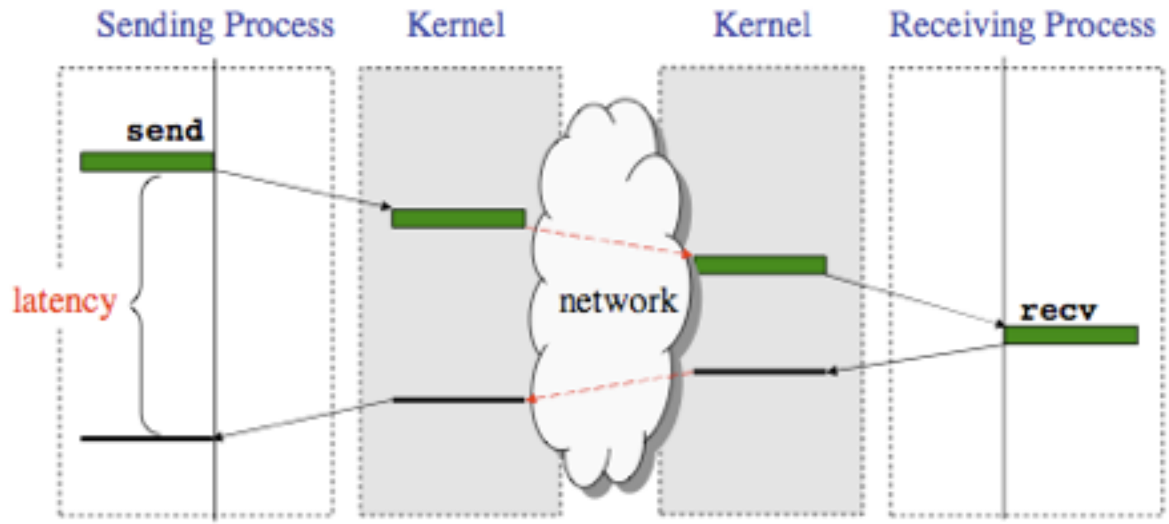
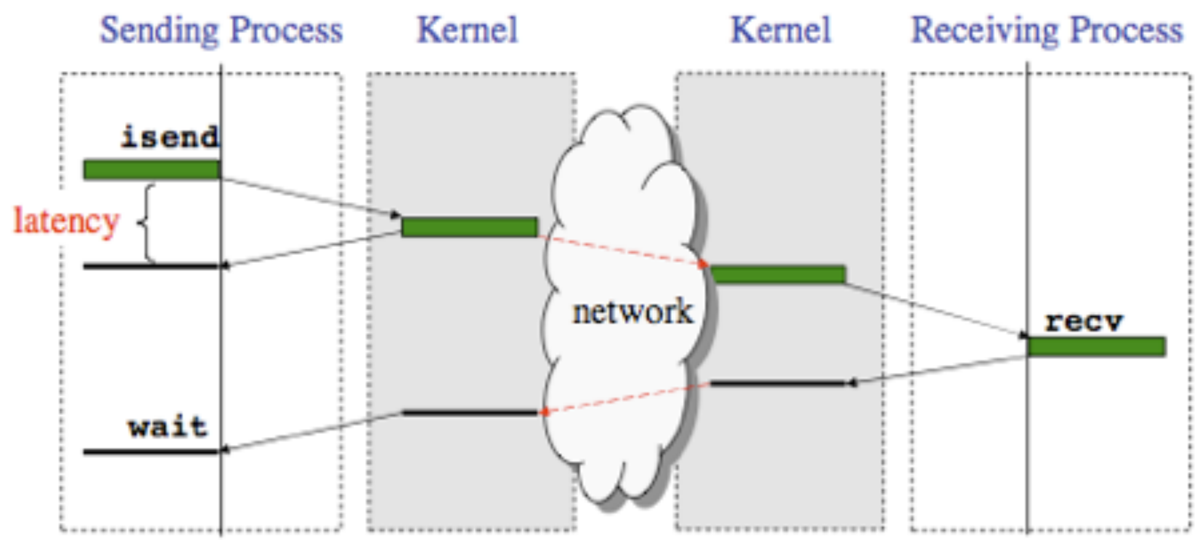
- **Blocking communications (contd)**
- **Non-blocking communications**
- **Collective communications**

Latency in Blocking vs. Nonblocking Communication

Blocking communication



Nonblocking communication (like an async or future task)



Non-Blocking Send and Receive operations

- In order to overlap communication with computation, MPI provides a pair of functions for performing non-blocking send and receive operations ("I" stands for "Immediate")

Request Isend(Object buf, int offset, int count, Datatype type, int dst, int tag) ;

Request Irecv(Object buf, int offset, int count, Datatype type, int src, int tag) ;

- Use Wait() to wait for operation to complete (like future get).

Status Wait(Request request)

- The Wait() operation is declared to return a Status object. In the case of a non-blocking receive operation, this object has the same interpretation as the Status object returned by a blocking Recv() operation.

Simple Irecv() example

- The simplest way of waiting for completion of a single non-blocking operation is to use the instance method Wait() in the Request class, e.g:

```
// Post a receive (like a "communication async")
Request request = Irecv(intBuf, 0, n, MPI.INT,
                        MPI.ANY_SOURCE,  0) ;
// Do some work while the receive is in progress
…
// Wait for message to arrive (like a future get)
Status status = request.Wait() ;
// Do something with data received in intBuf
…
```

Waitall() vs. Waitany()

public static Status[] Waitall (Request [] array_of_request)

- Waitall() blocks until all operations associated with the active requests have completed.
- Returns an array of statuses for each of the requests.
  — Waitall() is a like a finish scope for all requests in the array

public static Status Waitany(Request [] array_of_request)

- Waitany() blocks until one of the operations associated with the active requests has completed.
  —Source of nondeterminism

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Collective Communications

- A popular feature of MPI is its family of collective communication operations.
- Each collective operation is defined over a communicator (most often, MPI.COMM_WORLD)

— Each collective operation contains an *implicit barrier*. The operation completes and execution continues when all processes in the communicator perform the *same* collective operation.

— A mismatch in operations results in *deadlock* e.g.,

Process 0: .... MPI.Bcast(...) ....

Process 1: .... MPI.Bcast(...) ....

Process 2: .... MPI.Gather(...) ….

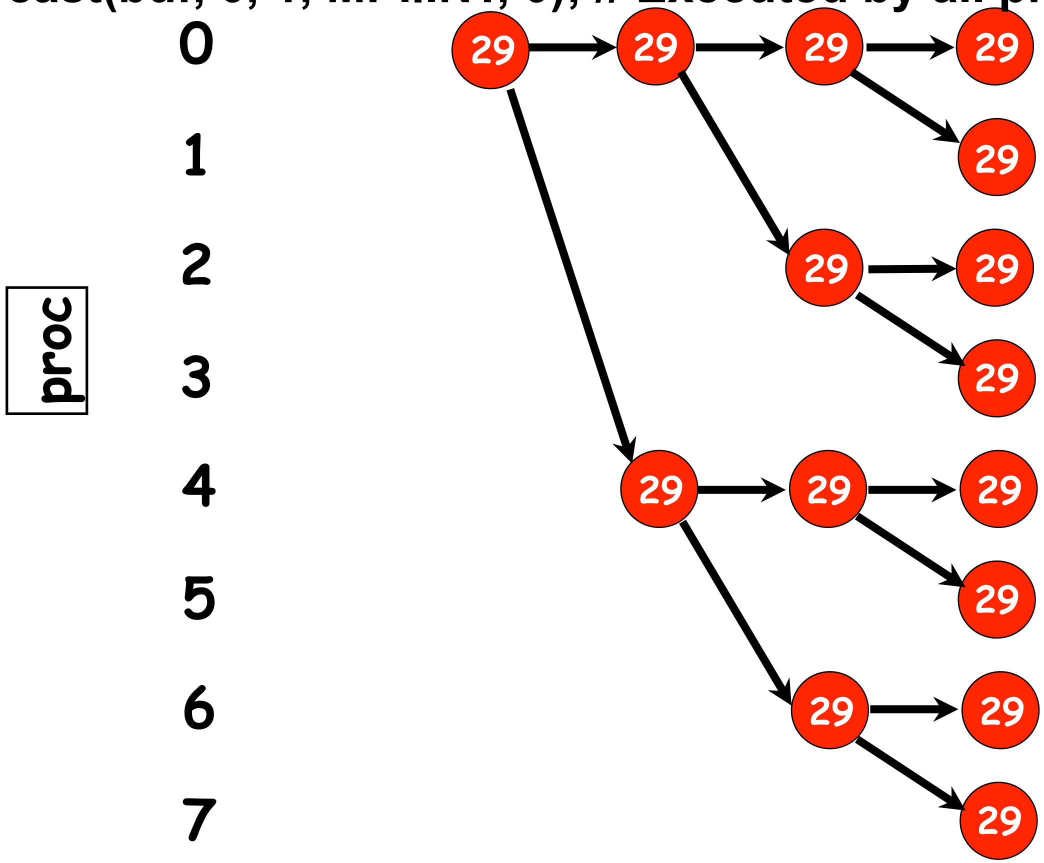
- A simple example is the broadcast operation: all processes invoke the operation, all agreeing on one root process. Data is broadcast from that root.

```
void Bcast(Object  buf, int  offset, int  count, Datatype type, int  root)
```

MPI_Bcast

buf = new int[1]; if (rank==0) buf[0] = 29;

void Bcast(buf, 0, 1, MPI.INT, 0); // Executed by all processes



A root process sends same message to all

29 represents an array of values

Broadcast can be implemented as a tree by MPI runtime

More Examples of Collective Operations

```
void Gather(Object sendbuf, int sendoffset, int sendcount,
  Datatype sendtype, Object recvbuf, int recvoffset, int recvcount,
  Datatype recvtype, int root)
```

- Each process sends the contents of its send buffer to the root process.

```
void Scatter(Object sendbuf, int sendoffset, int sendcount,
  Datatype sendtype, Object recvbuf, int recvoffset, int recvcount,
  Datatype recvtype, int root)
```

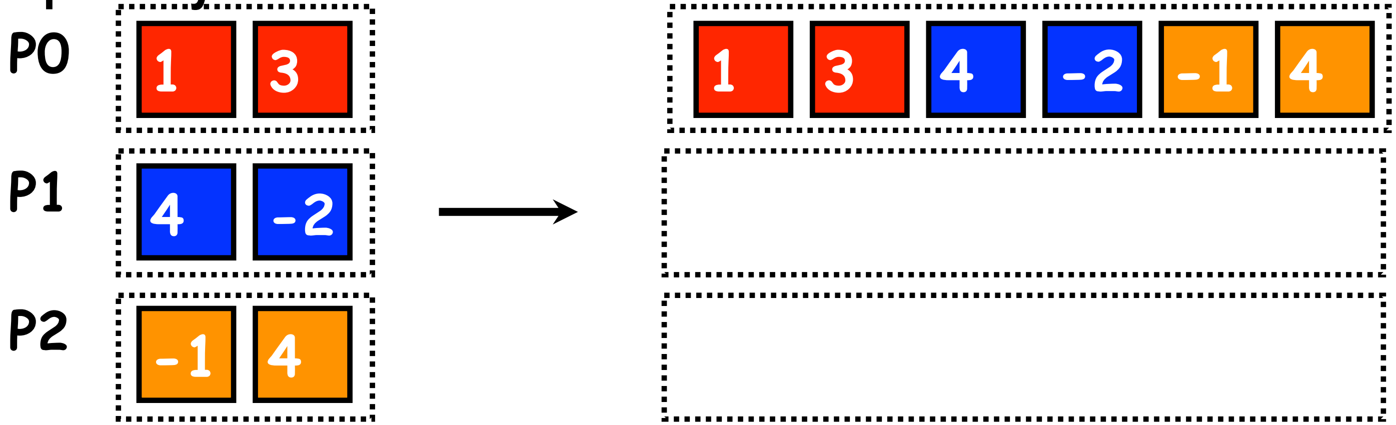
- Inverse of the operation Gather.

```
void Reduce(Object sendbuf, int sendoffset, Object recvbuf, int recvoffset,
  int count, Datatype datatype, Op op, int root)
```

- Combine elements in send buffer of each process using the reduce operation, and return the combined value in the receive buffer of the root process.

MPI_Gather

- Use to copy an array of data from each process into a single array on a single process.
- Graphically:



- Note: only process 0 (P0) needs to supply storage for the output

void Gather(Object sendbuf, int sendoffset, int sendcount,

Datatype sendtype, Object recvbuf, int recvoffset,

int recvcount, Datatype recvtype, int root)

– Each process sends the contents of its send buffer to the root process.

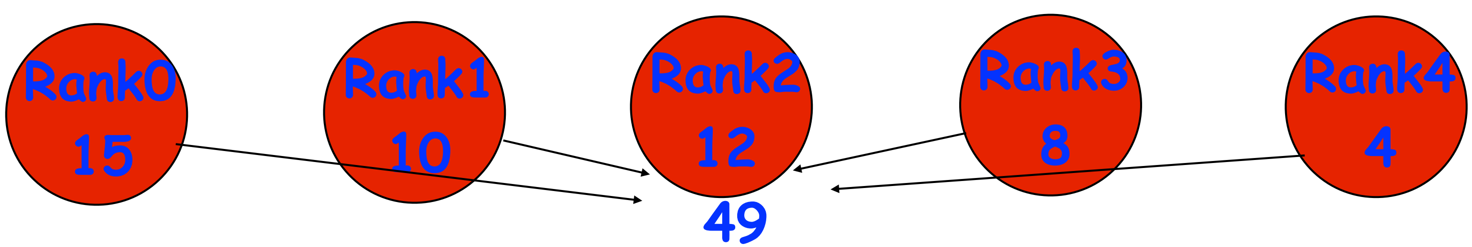
Predefined Reduction Operations

Operation	Meaning	Datatypes
`MPI_MAX`	Maximum	int, long, float, double
`MPI_MIN`	Minimum	int, long, float, double
`MPI_SUM`	Sum	int, long, float, double
`MPI_PROD`	Product	int, long, float, double
`MPI_LAND`	Logical AND	int, long
`MPI_BAND`	Bit-wise AND	byte, int, long
`MPI_LOR`	Logical OR	int, long
`MPI_BOR`	Bit-wise OR	byte, int, long
`MPI_LXOR`	Logical XOR	int, long
`MPI_BXOR`	Bit-wise XOR	byte, int, long
`MPI_MAXLOC`	max-min value-location	Data-pairs
`MPI_MINLOC`	min-min value-location	Data-pairs

MPI Reduce

void MPI.COMM_WORLD.Reduce(

Object	sendbuf	/* in */,
int	sendoffset	/* in */,
Object	recvbuf	/* out */,
int	recvoffset	/* in */,
int	count	/* in */,
MPI.Datatype	datatype	/* in */,
MPI.Op	operator	/* in */,
int	root	/* in */)



MPI.COMM_WORLD.Reduce(msg, 0, result, 0, 1, MPI.INT, MPI.SUM, 2);