Parallel Programming

Distributed-Memory Programming with MPI

(Part II)

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Acknowledgement

- This set of slides is mainly developed by Prof. Thomas Sterling and Dr. Steve Brandt from Louisiana State University

Review of Basic MPI Calls

- In review, the 6 main MPI calls:
  - MPI_Init
  - MPI_Finalize
  - MPI_Comm_size
  - MPI_Comm_rank
  - MPI_Send
  - MPI_Recv
- Include MPI Header file
  - #include "mpi.h"
- Basic MPI Datatypes
  - MPI_INT, MPI_FLOAT, ….

Collective Calls

- A communication pattern that encompasses all processes within a communicator is known as **collective communication**
- MPI has several collective communication calls, the most frequently used are:
  - Synchronization
    - Barrier
  - Communication
    - Broadcast
    - Gather & Scatter
    - All Gather
  - Reduction
    - Reduce
    - AllReduce

Topics

- MPI Collective Calls: Synchronization Primitives
- MPI Collective Calls: Communication Primitives
- MPI Collective Calls: Reduction Primitives
- Derived Datatypes: Introduction
- Derived Datatypes: Contiguous
- Derived Datatypes: Vector
- Derived Datatypes: Indexed
- Derived Datatypes: Struct
- Matrix-Vector multiplication : A Case Study
- MPI Profiling calls
- Additional Topics
- Summary

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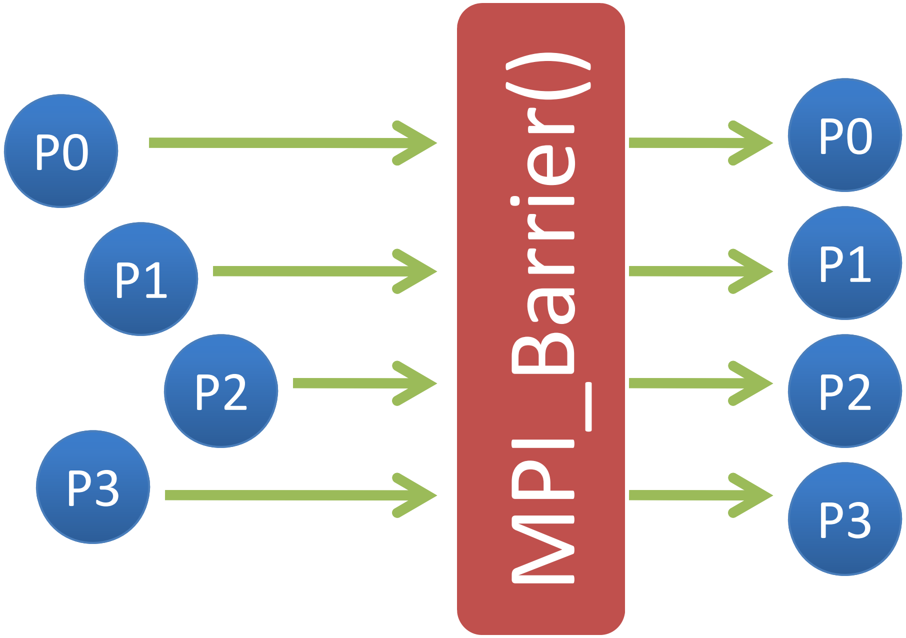
MPI Collective Calls : Barrier

Function: MPI_Barrier()

```
int MPI_Barrier (
        MPI_Comm comm )
```

Description:

Creates barrier synchronization in a communicator group *comm*. Each process, when reaching the MPI_Barrier call, blocks until all the processes in the group reach the same MPI_Barrier call.



http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Barrier.html

Example: MPI_Barrier()

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

int main (int argc, char *argv[]){
        int         rank, size, len;
        char         name[MPI_MAX_PROCESSOR_NAME];
        MPI_Init(&argc, &argv);
          MPI_Barrier(MPI_COMM_WORLD);

        MPI_Comm_rank(MPI_COMM_WORLD, &rank);
        MPI_Comm_size(MPI_COMM_WORLD, &size);
        MPI_Get_processor_name(name, &len);
          MPI_Barrier(MPI_COMM_WORLD);

        printf ("Hello world! Process %d of %d on %s\n", rank, size, name);
        MPI_Finalize();
        return 0;
}
```

```
[cdekate@celeritas collective]$ mpirun -np 8 barrier
Hello world! Process 0 of 8 on celeritas.cct.lsu.edu
Writing logfile....
Finished writing logfile.
Hello world! Process 4 of 8 on compute-0-3.local
Hello world! Process 1 of 8 on compute-0-0.local
Hello world! Process 3 of 8 on compute-0-2.local
Hello world! Process 6 of 8 on compute-0-5.local
Hello world! Process 7 of 8 on compute-0-6.local
Hello world! Process 5 of 8 on compute-0-4.local
Hello world! Process 2 of 8 on compute-0-1.local
[cdekate@celeritas collective]$
```

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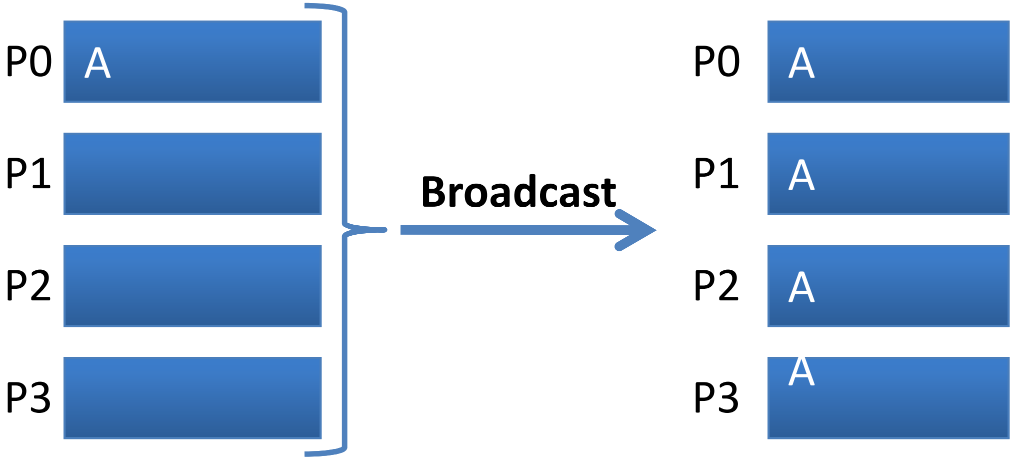
MPI Collective Calls : Broadcast

Function: MPI_Bcast()

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



Description:

A collective communication call where a single process sends the same data contained in the *message* to every process in the communicator. By default a tree like algorithm is used to broadcast the message to a block of processors, a linear algorithm is then used to broadcast the message from the first process in a block to all other processes. All the processes invoke the *MPI_Bcast* call with the same arguments for root and *comm*,

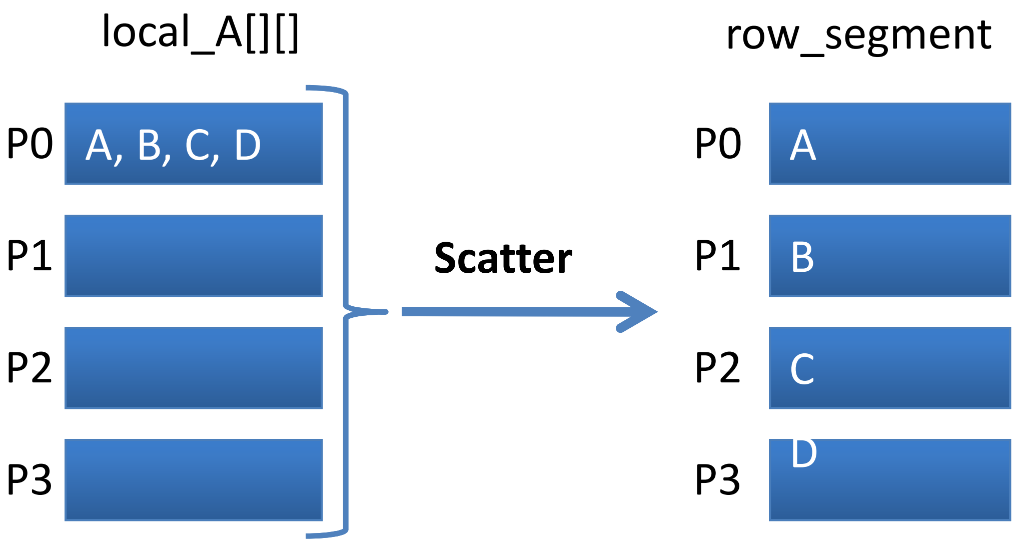
```
   float        endpoint[2];
  ...
   MPI_Bcast(endpoint, 2, MPI_FLOAT, 0, MPI_COMM_WORLD);
  ...
```

http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Bcast.html

MPI Collective Calls : Scatter

Function: MPI_Scatter()

```
int MPI_Scatter (
        void            *sendbuf,
        int             send_count,
        MPI_Datatype    send_type,
        void            *recvbuf,
        int             recv_count,
        MPI_Datatype    recv_type,
        int             root,
        MPI_Comm        comm)
```



Description:

http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Scatter.html

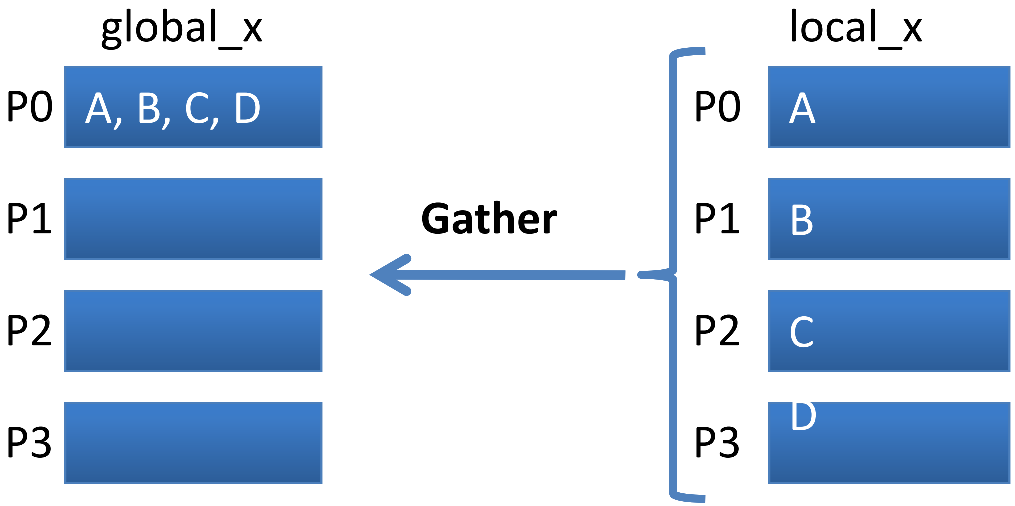
MPI_Scatter splits the data referenced by the *sendbuf* on the process with rank root into *p* segments each of which consists of *send_count* elements of type *send_type*. The first segment is sent to process0 and the second segment to process1.The send arguments are significant on the process with rank *root*.

```
...
MPI_Scatter(&(local_A[0][0]), n/p, MPI_FLOAT, row_segment, n/p, MPI_FLOAT, 0,MPI_COMM_WORLD);
...
```

MPI Collective Calls : Gather

Function: MPI_Gather()

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



Description: http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Gather.html

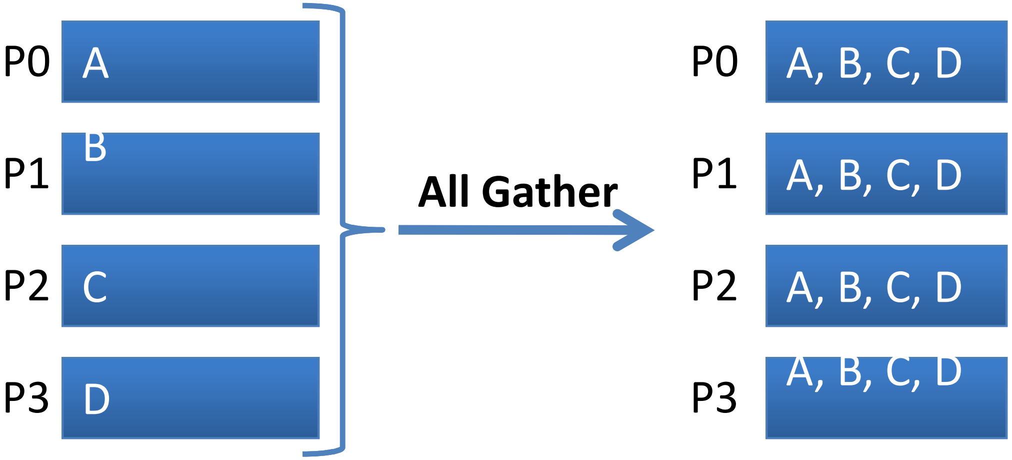
MPI_Gather collects the data referenced by *sendbuf* from each process in the communicator *comm*, and stores the data in process rank order on the process with rank *root* in the location referenced by *recvbuf*.The *recv* parameters are only significant.

```
...
    MPI_Gather(local_x, n/p, MPI_FLOAT, global_x, n/p, MPI_FLOAT, 0, MPI_COMM_WORLD);
...
```

MPI Collective Calls : All Gather

Function: MPI_Allgather()

```
int MPI_Allgather (
     void              *sendbuf,
     int               send_count,
     MPI_Datatype      sendtype,
     void              *recvbuf,
     int               recvcount,
     MPI_Datatype      recvtype,
     MPI_Comm          comm )
```



http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Allgather.html

Description:

MPI_Allgather gathers the content from the send buffer (*sendbuf*) on each process. The effect of this call is similar to executing MPI_Gather() p times with a different process acting as the root.

```
 for (root=0; root<p; root++)
    MPI_Gather(local_x, n/p, MPI_FLOAT, global_x, n/p, MPI_FLOAT, root, MPI_COMM_WORLD);
. . .
```

CAN BE REPLACED WITH :

```
MPI_Allgather(local_x, local_n, MPI_FLOAT, global_x, local_n, MPI_FLOAT, MPI_COMM_WORLD);
```

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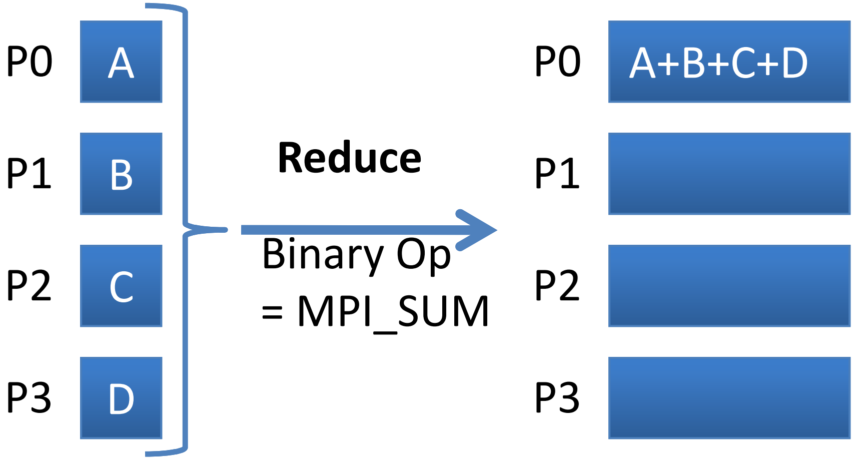
MPI Collective Calls : Reduce

Function: MPI_Reduce()

```
int MPI_Reduce (
    void            *operand,
    void            *result,
    int             count,
    MPI_Datatype datatype,
    MPI_Op          operator,
    int             root,
    MPI_Comm        comm )
```



http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Reduce.html

Description:

A collective communication call where all the processes in a communicator contribute data that is combined using binary operations (MPI_Op) such as addition, max, min, logical, and, etc. MPI_Reduce combines the operands stored in the memory referenced by *operand* using the operation *operator* and stores the result in **result*. MPI_Reduce is called by all the processes in the communicator *comm* and for each of the processes *count, datatype operator* and *root* remain the same.

```
. . .
MPI_Reduce(&local_integral, &integral, 1, MPI_FLOAT, MPI_SUM, 0, MPI_COMM_WORLD);
. . .
```

MPI Binary Operations

- MPI binary operators are used in the MPI_Reduce function call as one of the parameters. MPI_Reduce performs a global reduction operation (dictated by the MPI binary operator parameter) on the supplied operands.
- Some of the common MPI Binary Operators used are :

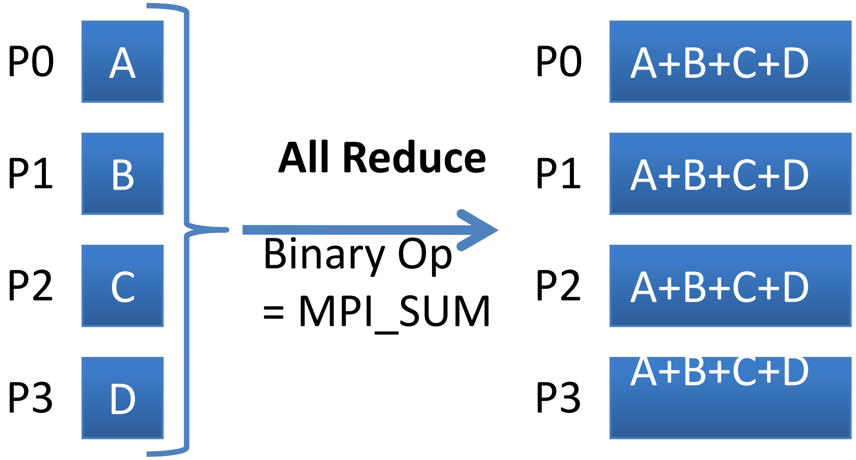
Operation Name	Meaning
MPI_MAX	Maximum
MPI_MIN	Minimum
MPI_SUM	Sum
MPI_PROD	Product
MPI_LAND	Logical And
MPI_BAND	Bitwise And
MPI_LOR	Logical Or
MPI_BOR	Bitwise Or
MPI_LXOR	Logical XOR
MPI_BXOR	Bitwise XOR
MPI_MAXLOC	Maximum and location of max.
MPI_MINLOC	Maximum and location of min.

```
 MPI_Reduce(&local_integral,
&integral, 1, MPI_FLOAT,
MPI_SUM, 0,
MPI_COMM_WORLD);
```

MPI Collective Calls : All Reduce

Function:	MPI_Allreduce()

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



Description:

MPI_Allreduce is used exactly like MPI_Reduce, except that the result of the reduction is returned on all processes, as a result there is no *root* parameter.

```
...
MPI_Allreduce(&integral, &integral, 1, MPI_FLOAT, MPI_SUM, MPI_COMM_WORLD);
...
```

http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Allreduce.html

Parallel Trapezoidal Rule
Send, Recv

```
#include <stdio.h>
#include "mpi.h”

main(int argc, char** argv) {
   int       my_rank;   /* My process rank           */
   int       p;         /* The number of processes   */
   float     a = 0.0;   /* Left endpoint             */
   float     b = 1.0;   /* Right endpoint            */
   int       n = 1024;  /* Number of trapezoids      */
   float     h;         /* Trapezoid base length     */
   float     local_a;   /* Left endpoint my process  */
   float     local_b;   /* Right endpoint my process */
   int       local_n;   /* Number of trapezoids for my
calculation            */
   float     integral;  /* Integral over my interval */
   float     total;     /* Total integral            */
   int       source;    /* Process sending integral  */
   int       dest = 0;  /* All messages go to 0      */
   int       tag = 0;
   MPI_Status  status;
```

```
float Trap(float local_a, float local_b, int local_n,
          float h);    /* Calculate local integral  */

/* Let the system do what it needs to start up MPI */
MPI_Init(&argc, &argv);

/* Get my process rank */
MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);

/* Find out how many processes are being used */
MPI_Comm_size(MPI_COMM_WORLD, &p);

h = (b-a)/n;    /* h is the same for all processes */
local_n = n/p;  /* So is the number of trapezoids */

/* Length of each process' interval of
 * integration = local_n*h.  So my interval
 * starts at: */
local_a = a + my_rank*local_n*h;
local_b = local_a + local_n*h;
integral = Trap(local_a, local_b, local_n, h);
```

Trapezoidal Example Adapted from Parallel Programming in MPI P.Pacheco Ch 4

Parallel Trapezoidal Rule
Send, Recv

```
if (my_rank == 0) {
        total = integral;
        for (source = 1; source < p; source++) {
               MPI_Recv(&integral, 1, MPI_FLOAT, source, tag,
                    MPI_COMM_WORLD, &status);
               total = total + integral;
        }
    } else {
          MPI_Send(&integral, 1, MPI_FLOAT, dest,
               tag, MPI_COMM_WORLD);
    }
if (my_rank == 0) {
        printf("With n = %d trapezoids, our estimate\n",
            n);
        printf("of the integral from %f to %f = %f\n",
            a, b, total);
    }
MPI_Finalize();
} /*  main  */
```

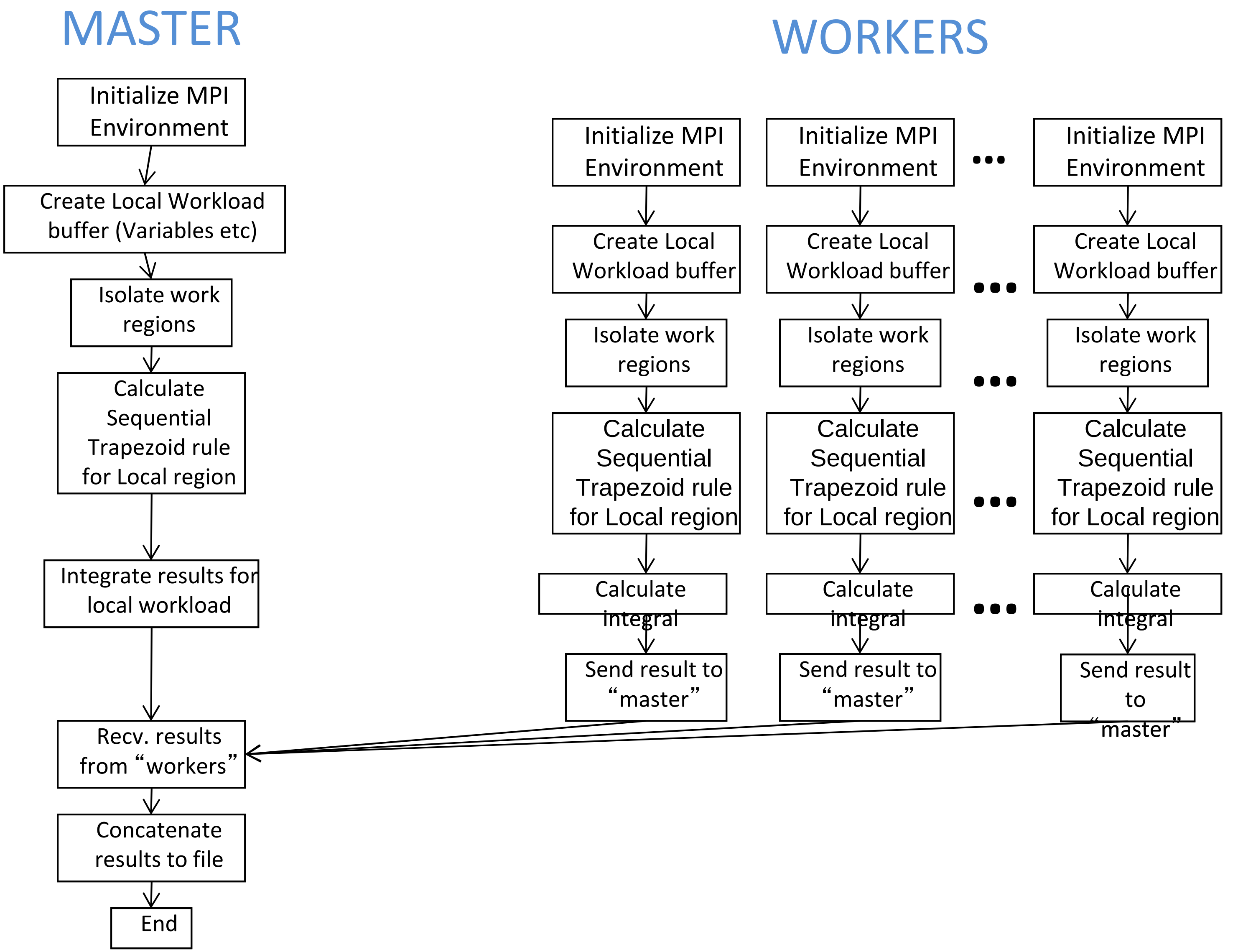
Trapezoidal Example Adapted from Parallel Programming in MPI P.Pacheco Ch 4

Parallel Trapezoidal Rule
Send, Recv

```
float Trap(
        float  local_a   /* in */,
        float  local_b   /* in */,
        int    local_n   /* in */,
        float  h         /* in */) {

   float integral;   /* Store result in integral  */
   float x;
   int i;

   float f(float x); /* function we're integrating */

   integral = (f(local_a) + f(local_b))/2.0;
   x = local_a;
   for (i = 1; i <= local_n-1; i++) {
      x = x + h;
      integral = integral + f(x);
   }
   integral = integral*h;
   return integral;
} /*  Trap  */
float f(float x) {
   float return_val;
   /* Calculate f(x). */
   /* Store calculation in return_val. */
   return_val = x*x;
   return return_val;
} /* f */
```

Trapezoidal Example Adapted from Parallel Programming in MPI P.Pacheco Ch 4

Flowchart for Parallel Trapezoidal Rule



MASTER

Initialize MPI Environment

Create Local Workload buffer (Variables etc)

Isolate work regions

Calculate Sequential Trapezoid rule for Local region

Integrate results for local workload

Recv. results from "workers"

Concatenate results to file

End

WORKERS

Initialize MPI Environment

Create Local Workload buffer

Isolate work regions

Calculate Sequential Trapezoid rule for Local region

Calculate integral

Send result to "master"

…

Trapezoidal Rule : with MPI_Bcast, MPI_Reduce

```
#include <stdio.h>
#include <stdlib.h>

/* We'll be using MPI routines, definitions, etc. */
#include "mpi.h"


main(int argc, char** argv) {
   int       my_rank;   /* My process rank           */
   int       p;         /* The number of processes   */
   float     endpoint[2];  /* Left and right         */
   int       n = 1024;  /* Number of trapezoids      */
   float     h;         /* Trapezoid base length     */
   float     local_a;   /* Left endpoint my process  */
   float     local_b;   /* Right endpoint my process */
   int       local_n;   /* Number of trapezoids for  */
                        /* my calculation            */
   float     integral;  /* Integral over my interval */
   float     total;     /* Total integral            */
   int       source;    /* Process sending integral  */
   int       dest = 0;  /* All messages go to 0      */
   int       tag = 0;
   MPI_Status  status;
```

```
float Trap(float local_a, float local_b, int local_n,
          float h);    /* Calculate local integral  */

   MPI_Init(&argc, &argv);
   MPI_Comm_rank(MPI_COMM_WORLD, &my_rank);
   MPI_Comm_size(MPI_COMM_WORLD, &p);

   if (argc != 3) {
     if (my_rank==0)
                printf("Usage:  mpirun -np <numprocs> trapezoid
<left> <right>\n");
     MPI_Finalize();
     exit(0);
   }

   if (my_rank==0) {
     endpoint[0] = atof(argv[1]);   /*  left endpoint */
     endpoint[1] = atof(argv[2]);   /* right endpoint */
   }
```

```
MPI_Bcast(endpoint, 2, MPI_FLOAT,
0, MPI_COMM_WORLD);
```

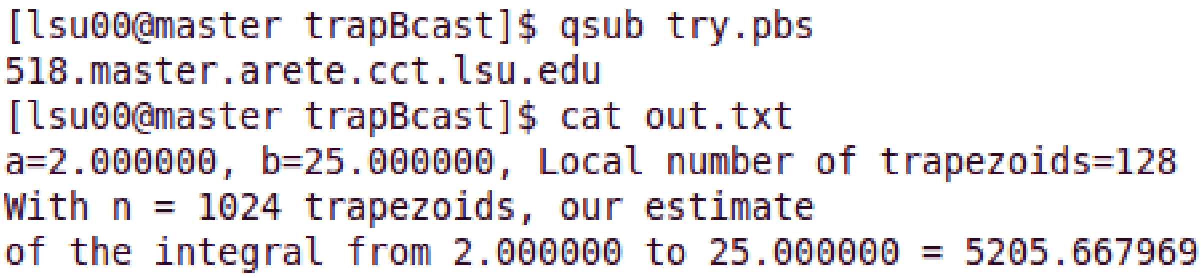
Trapezoidal Rule : with MPI_Bcast, MPI_Reduce

```
   h = (endpoint[1]-endpoint[0])/n;    /* h is the same for all processes
*/
   local_n = n/p;                    /*  so is the number of trapezoids */
   if (my_rank == 0) printf("a=%f, b=%f, Local number of
trapezoids=%d\n", endpoint[0], endpoint[1], local_n );

   local_a = endpoint[0] + my_rank*local_n*h;
   local_b = local_a + local_n*h;
   integral = Trap(local_a, local_b, local_n, h);

MPI_Reduce(&integral, &total, 1,
MPI_FLOAT, MPI_SUM, 0,
MPI_COMM_WORLD);

if (my_rank == 0) {
      printf("With n = %d trapezoids, our estimate\n",
         n);
      printf("of the integral from %f to %f = %f\n",
         endpoint[0], endpoint[1], total);
   }

MPI_Finalize();
} /*  main  */
```

```
float Trap(
        float  local_a   /* in */,
        float  local_b   /* in */,
        int    local_n   /* in */,
        float  h         /* in */) {

   float integral;   /* Store result in integral  */
   float x;
   int i;

   float f(float x); /* function we're integrating */

   integral = (f(local_a) + f(local_b))/2.0;
   x = local_a;
   for (i = 1; i <= local_n-1; i++) {
      x = x + h;
      integral = integral + f(x);
   }
   integral = integral*h;
   return integral;
} /*  Trap  */


float f(float x) {
   float return_val;
   /* Calculate f(x). */
   /* Store calculation in return_val. */
   return_val = x*x;
   return return_val;
} /* f */
```

Trapezoidal Rule : with MPI_Bcast, MPI_Reduce

```
#!/bin/bash
#PBS -N name
#PBS -l walltime=120:00:00,nodes=2:ppn=4
cd /home/lsu00/Demos/l9/trapBcast
pwd
date
PROCS=`wc -l < $PBS_NODEFILE`
mpdboot --file=$PBS_NODEFILE
/usr/lib64/mpich2/bin/mpiexec -n $PROCS ./trapBcast 2 25 >>out.txt
mpdallexit
date
```



```
[lsu00@master trapBcast]$ qsub try.pbs
518.master.arete.cct.lsu.edu
[lsu00@master trapBcast]$ cat out.txt
a=2.000000, b=25.000000, Local number of trapezoids=128
With n = 1024 trapezoids, our estimate
of the integral from 2.000000 to 25.000000 = 5205.667969
```

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Consolidating Data

- In virtually all distributed-memory systems, communication can be much more expensive than local computation
- We would expect the following pair of **for** loops to be much slower than the single send/receive pair

```
double x[1000];
. . .
if (my_rank == 0)
   for (i = 0; i < 1000; i++)
      MPI_Send(&x[i], 1, MPI_DOUBLE, 1, 0, comm);
else /* my_rank == 1 */
   for (i = 0; i < 1000; i++)
      MPI_Recv(&x[i], 1, MPI_DOUBLE, 0, 0, comm, &status);

if (my_rank == 0)
   MPI_Send(x, 1000, MPI_DOUBLE, 1, 0, comm);
else  /* my_rank == 1 */
   MPI_Recv(x, 1000, MPI_DOUBLE, 0, 0, comm, &status);
```

Consolidating Data (Cont’d)

- MPI provides three basic approaches to consolidating data that might otherwise require multiple messages:
  - the count argument to the various communication functions,
  - derived datatypes, and
  - MPI_Pack/Unpack (see Exercise 3.20)

Constructing Datatypes

- Creating data structures in C:

```
typedef struct {
          . . .
 } STRUCT_NAME
```

- For example : In the numerical integration by trapezoidal rule we could create a data structure for storing the attributes of the problem as follows:

```
typedef struct {
     float a,
     float b,
     int n;
  } DATA_INTEGRAL;
   . . .
   . . .
   DATA_INTEGRAL intg_data;
```

- What would happen when you use:

ERROR!!!
Intg_data is of the type
DATA_INTEGRAL
NOT an MPI_Datatype

```
MPI_Bcast( &intg_data, 1, DATA_INTEGRAL, 0, MPI_COMM_WORLD);
```

Constructing MPI Datatypes

- MPI allows users to define derived MPI datatypes, using basic datatypes that build during execution time
- These derived data types can be used in the MPI communication calls, instead of the basic predefined datatypes.
- A sending process can pack noncontiguous data into contiguous buffer and send the buffered data to a receiving process that can unpack the contiguous buffer and store the data to noncontiguous location.
- A derived datatype is an opaque object that specifies :
  - A sequence of primitive datatypes
  - A sequence of integer (byte) displacements
- MPI has several functions for constructing derived datatypes :
  - Contiguous
  - Vector
  - Indexed
  - Struct

MPI : Basic Data Types (Review)

MPI datatype	C datatype
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_BYTE	
MPI_PACKED	

You can also define your own (derived datatypes), such as an array of ints of size 100, or more complex examples, such as a struct or an array of structs

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Derived Datatypes : Contiguous

Function: MPI_Type_contiguous()

```
int MPI_Type_contiguous(
        int count,
        MPI_Datatype old_type,
        MPI_Datatype *new_type)
```

Description:

This is the simplest constructor in the MPI derived datatypes. Contiguous datatype constructors create a new datatype by making *count* copies of existing data type (*old_type*)

```
MPI_Datatype rowtype;
...
MPI_Type_contiguous(SIZE, MPI_FLOAT, &rowtype);
MPI_Type_commit(&rowtype);
...
```

http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Type_contiguous.html

Example : Derived Datatypes - Contiguous

```
#include "mpi.h"
#include <stdio.h>
#define SIZE 4

int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, source=0, dest, tag=1, i;
MPI_Request req;
float a[SIZE][SIZE] =
  {1.0, 2.0, 3.0, 4.0,
   5.0, 6.0, 7.0, 8.0,
   9.0, 10.0, 11.0, 12.0,
   13.0, 14.0, 15.0, 16.0};
float b[SIZE];

MPI_Status stat;
MPI_Datatype rowtype;
```

```
MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
MPI_Type_contiguous(SIZE, MPI_FLOAT,
&rowtype);
MPI_Type_commit(&rowtype);
if (numtasks == SIZE) {
  if (rank == 0) {
     for (i=0; i<numtasks; i++){
          dest = i;
         MPI_Isend(&a[i][0], 1, rowtype, dest,
tag, MPI_COMM_WORLD, &req);
     }
  }
   MPI_Recv(b, SIZE, MPI_FLOAT, source, tag,
MPI_COMM_WORLD, &stat);
  printf(“rank= %d  b= %3.1f %3.1f %3.1f %3.1f\n”,
         rank,b[0],b[1],b[2],b[3]);
  }
else
  printf(“Must specify %d processors. Terminating.\n”,SIZE);
MPI_Type_free(&rowtype);
MPI_Finalize();
}
```

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatypes - Contiguous

1.0	2.0	3.0	4.0
5.0	6.0	7.0	8.0
9.0	10.0	11.0	12.0
13.0	14.0	15.0	16.0

Declares a 4x4 array of datatype **float**

```
#include "mpi
#include <stdi
#define SI

int main(argc,
int argc;
char *argv[];
int numtasks,
MPI_Request re
float a[SIZE][SIZE] =
  {1.0, 2.0, 3.0, 4.0,
   5.0, 6.0, 7.0, 8.0,
   9.0, 10.0, 11.0, 12.0,
   13.0, 14.0, 15.0, 16.0};
float b[SIZE];

MPI_Status stat;
MPI_Datatype rowtype;
```

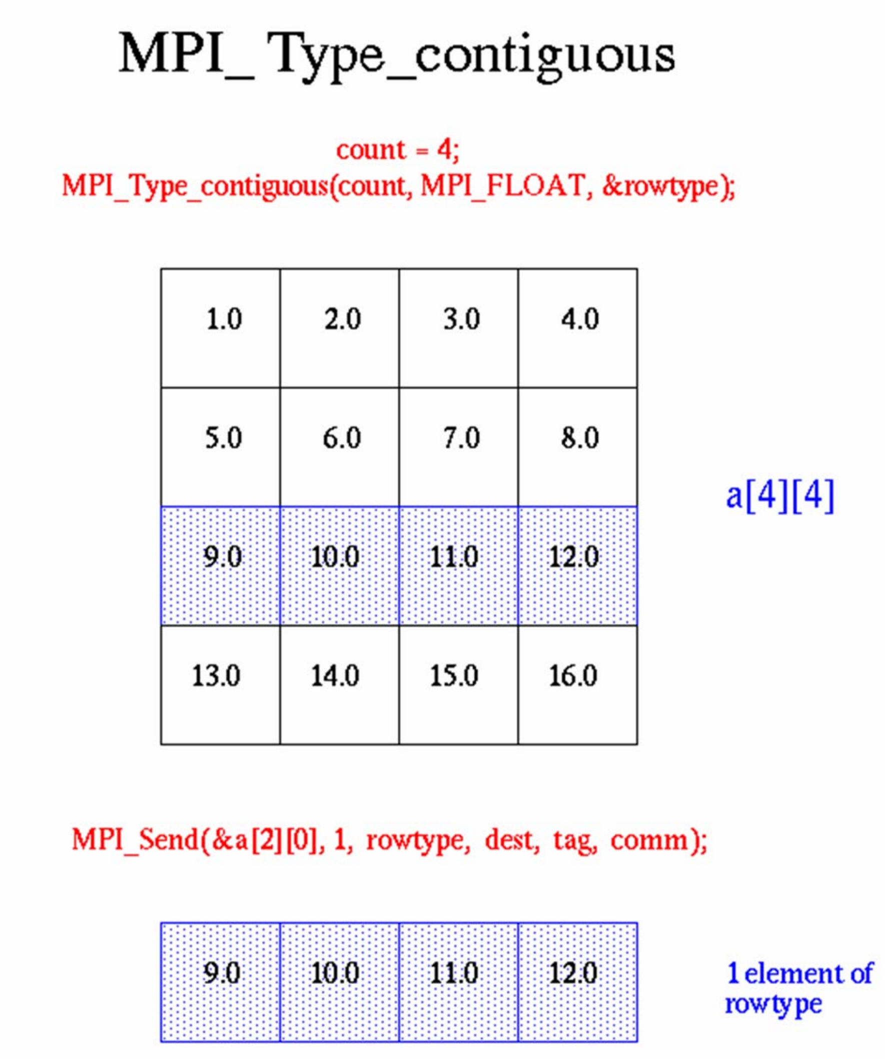
```
I_Init(&argc,&argv);
I_Comm_rank(MPI_COMM_WORLD, &rank);
I_Comm_size(MPI_COMM_WORLD, &numtasks);
PI_Type_contiguous(SIZE, MPI_FLOAT,
rowtype);
PI_Type_commi
 (numtasks == SI
 if (rank == 0) {
    for (i=0; i<n
         dest = i
        MPI_Ise                                  dest,
tag, MPI_COMM_
      }
  }
   MPI_Recv(b,                                   tag,
MPI_COMM_WORLD
  printf(“rank= %d
         rank,b[0],b[1],b[2],b[3]);
  }
else
  printf(“Must specify %d processors. Terminating.\n”,SIZE);
MPI_Type_free(&rowtype);
MPI_Finalize();
}
```

1.0	2.0	3.0	4.0
5.0	6.0	7.0	8.0
9.0	10.0	11.0	12.0
13.0	14.0	15.0	16.0

Homogenous datastructure of size 4 (Type : *rowtype*)

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatypes - Contiguous



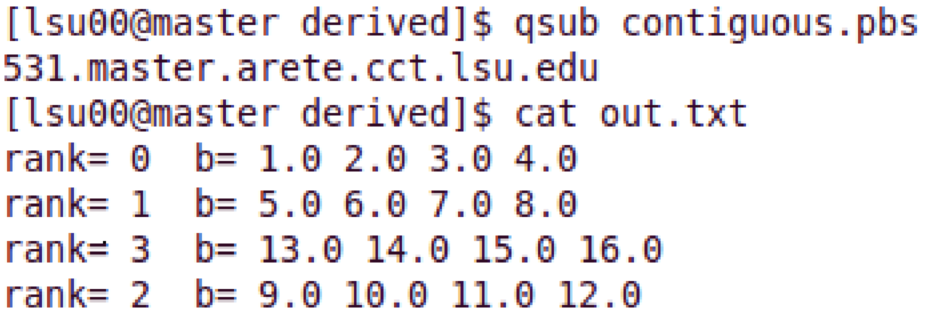
MPI_ Type_contiguous

```
count = 4;
MPI_Type_contiguous(count, MPI_FLOAT, &rowtype);
```

1.0	2.0	3.0	4.0
5.0	6.0	7.0	8.0
9.0	10.0	11.0	12.0
13.0	14.0	15.0	16.0

```
MPI_Send(&a[2][0], 1, rowtype, dest, tag, comm);
```

9.0	10.0	11.0	12.0



```
[lsu00@master derived]$ qsub contiguous.pbs
531.master.arete.cct.lsu.edu
[lsu00@master derived]$ cat out.txt
rank= 0  b= 1.0 2.0 3.0 4.0
rank= 1  b= 5.0 6.0 7.0 8.0
rank= 3  b= 13.0 14.0 15.0 16.0
rank= 2  b= 9.0 10.0 11.0 12.0
```

https://computing.llnl.gov/tutorials/mpi/

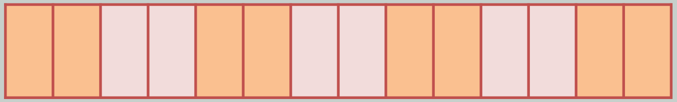
Topics

- MPI Collective Calls: Synchronization Primitives
- MPI Collective Calls: Communication Primitives
- MPI Collective Calls: Reduction Primitives
- Derived Datatypes: Introduction
- Derived Datatypes: Contiguous
- Derived Datatypes: Vector
- Derived Datatypes: Indexed
- Derived Datatypes: Struct
- Matrix-Vector multiplication : A Case Study
- MPI Profiling calls
- Additional Topics
- Summary

Derived Datatypes : Vector

Function: MPI_Type_vector()

```
int MPI_Type_vector(
        int count,
        int blocklen,
        int stride,
        MPI_Datatype old_type,
        MPI_Datatype *newtype )
```



count = 4
blocklen = 2
stride = 4

Description:
Returns a new datatype that represents equally spaced blocks. The spacing between the start of each block is given in units of extent (oldtype). The *count* represents the number of blocks, *blocklen* details the number of elements in each block, stride represents the number of elements between start of each block of the *old_type*. The new datatype is stored in *new_type*

```
...
MPI_Type_vector(SIZE, 1, SIZE, MPI_FLOAT, &columntype);
...
```

http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Type_vector.html

Example : Derived Datatypes - Vector

```
#include "mpi.h"
#include <stdio.h>
#define SIZE 4

int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, source=0, dest, tag=1, i;
MPI_Request req;
float a[SIZE][SIZE] =
  {1.0, 2.0, 3.0, 4.0,
   5.0, 6.0, 7.0, 8.0,
   9.0, 10.0, 11.0, 12.0,
  13.0, 14.0, 15.0, 16.0};
float b[SIZE];

MPI_Status stat;
MPI_Datatype columntype;
```

```
MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);

MPI_Type_vector(SIZE, 1, SIZE, MPI_FLOAT, &columntype);
MPI_Type_commit(&columntype);

if (numtasks == SIZE) {
  if (rank == 0) {
     for (i=0; i<numtasks; i++)
        MPI_Isend(&a[0][i], 1, columntype, i, tag,
MPI_COMM_WORLD, &req);
       }

  MPI_Recv(b, SIZE, MPI_FLOAT, source, tag,
MPI_COMM_WORLD, &stat);
  printf("rank= %d  b= %3.1f %3.1f %3.1f %3.1f\n",
       rank,b[0],b[1],b[2],b[3]);
  }
else
  printf("Must specify %d processors. Terminating.\n",SIZE);

MPI_Type_free(&columntype);
MPI_Finalize();
}
```

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatypes - Vector

```
#include "mpi.h"
#include <stdio.h>
#define SIZE 4

int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank,
MPI_Request req;
float a[SIZE][SIZE] =
  {1.0, 2.0, 3.0, 4.0,
   5.0, 6.0, 7.0, 8.0,
   9.0, 10.0, 11.0, 12.0,
  13.0, 14.0, 15.0, 16.0};
float b[SIZE];

MPI_Status stat;
MPI_Datatype columntype;
```

1.0	2.0	3.0	4.0
5.0	6.0	7.0	8.0
9.0	10.0	11.0	12.0
13.0	14.0	15.0	16.0

Declares a 4x4 array of datatype **float**

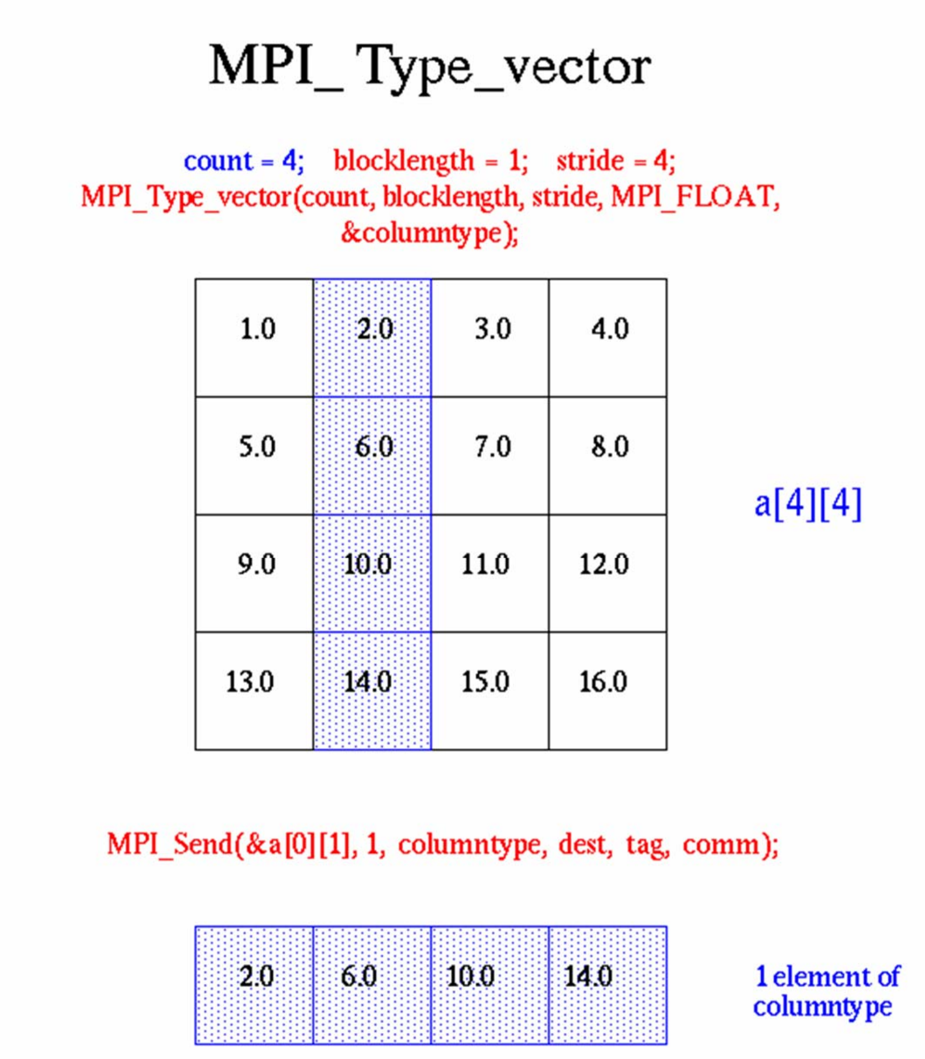
```
gc,&argv);
rank(MPI_COMM_WORLD, &rank);
size(MPI_COMM_WORLD, &numtasks);

_vector(SIZE, 1, SIZE, MPI_FLOAT, &columntype);
mmit(&columntype);

== SIZE) {
) {
numtasks; i++)
      MPI_Isend(&a[0][i
MPI_COMM_WORLD,
      }

 MPI_Recv(b, SIZE, MP
MPI_COMM_WORLD,
 printf("rank= %d  b= %3.1f %3
      rank,b[0],b[1],b[2],b[3]);
 }
else
 printf("Must specify %d processors. Terminating.\n",SIZE);

MPI_Type_free(&columntype);
MPI_Finalize();
}
```

1.0	2.0	3.0	4.0
5.0	6.0	7.0	8.0
9.0	10.0	11.0	12.0
13.0	14.0	15.0	16.0

Homogenous datastructure of size 4 (Type : *columntype*)

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatypes - Vector



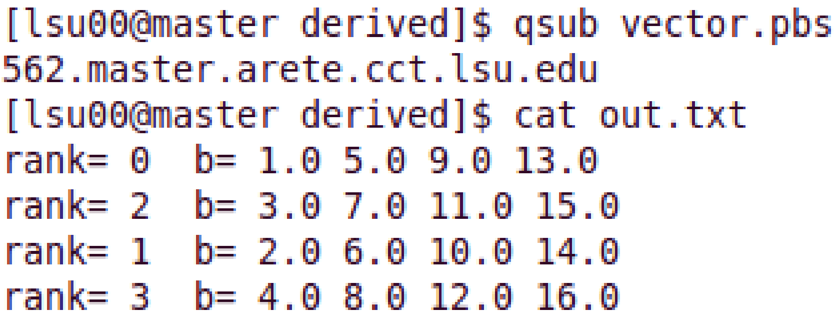
MPI_ Type_vector

```
count = 4;    blocklength = 1;    stride = 4;
MPI_Type_vector(count, blocklength, stride, MPI_FLOAT,
                &columntype);
```

1.0	2.0	3.0	4.0
5.0	6.0	7.0	8.0
9.0	10.0	11.0	12.0
13.0	14.0	15.0	16.0

```
MPI_Send(&a[0][1], 1, columntype, dest, tag, comm);
```

2.0	6.0	10.0	14.0



```
[lsu00@master derived]$ qsub vector.pbs
562.master.arete.cct.lsu.edu
[lsu00@master derived]$ cat out.txt
rank= 0  b= 1.0 5.0 9.0 13.0
rank= 2  b= 3.0 7.0 11.0 15.0
rank= 1  b= 2.0 6.0 10.0 14.0
rank= 3  b= 4.0 8.0 12.0 16.0
```

https://computing.llnl.gov/tutorials/mpi/

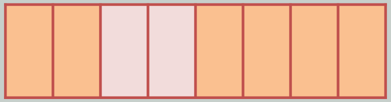
Topics

- MPI Collective Calls: Synchronization Primitives
- MPI Collective Calls: Communication Primitives
- MPI Collective Calls: Reduction Primitives
- Derived Datatypes: Introduction
- Derived Datatypes: Contiguous
- Derived Datatypes: Vector
- Derived Datatypes: Indexed
- Derived Datatypes: Struct
- Matrix-Vector multiplication : A Case Study
- MPI Profiling calls
- Additional Topics
- Summary

Derived Datatypes : Indexed

Function: MPI_Type_indexed()

```
int MPI_Type_indexed(
        int count,
        int *array_of_blocklengths,
        int *array_of_displacements,
        MPI_Datatype oldtype,
        MPI_datatype *newtype);
```



count = 2
array_of_blockengths[2] = {2, 4}
array_of_displacements[2] = {0, 4}

Description:

Returns a new datatype that represents count blocks. Each block is defined by an entry in *array_of_blocklengths* and *array_of_displacements*. Displacements are expressed in units of extent(oldtype). The *count* is the number of blocks and the number of entries in *array_of_displacements* (displacement of each block in units of the *oldtype*) and *array_of_blocklengths* (number of instances of *oldtype* in each block).

```
 ...
 MPI_Type_indexed(2, blocklengths, displacements, MPI_FLOAT,
&indextype);
 ...
```

https://computing.llnl.gov/tutorials/mpi/man/MPI_Type_indexed.txt

Example : Derived Datatypes - Indexed

```
#include "mpi.h"
#include <stdio.h>
#define NELEMENTS 6

int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, source=0, dest, tag=1, i;
MPI_Request req;
int blocklengths[2], displacements[2];
float a[16] =
  {1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0,
   9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0};
float b[NELEMENTS];

MPI_Status stat;
MPI_Datatype indextype;

MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
```

```
blocklengths[0] = 4;
blocklengths[1] = 2;
displacements[0] = 5;
displacements[1] = 12;

MPI_Type_indexed(2, blocklengths,
displacements, MPI_FLOAT, &indextype);
MPI_Type_commit(&indextype);

if (rank == 0) {
  for (i=0; i<numtasks; i++)
     MPI_Isend(a, 1, indextype, i, tag,
MPI_COMM_WORLD, &req);
  }

MPI_Recv(b, NELEMENTS, MPI_FLOAT, source,
tag, MPI_COMM_WORLD, &stat);
printf("rank= %d  b= %3.1f %3.1f %3.1f %3.1f %3.1f %3.1f\n",
    rank,b[0],b[1],b[2],b[3],b[4],b[5]);

MPI_Type_free(&indextype);
MPI_Finalize();
}
```

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatypes - Indexed

```
#include "mpi.h"
#include <stdio.h>
#define NELEMENTS 6
```

1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0

Declares a[16] array of type float

```
MPI_Request r
int blocklengths[2], displacements[2];
float a[16] =
  {1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0,
   9.0, 10.0, 11.0, 12.0, 13.0, 14.0, 15.0, 16.0};
float b[NELEMENTS];

MPI_Status stat;
MPI_Datatype indextype;

MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
```

```
blocklengths[0] = 4;
blocklengths[1] = 2;
displacements[0] = 5;
displacements[1] = 12;

lexed(2, blocklengths,
s, MPI_FLOAT, &indextype);
dextype);
```

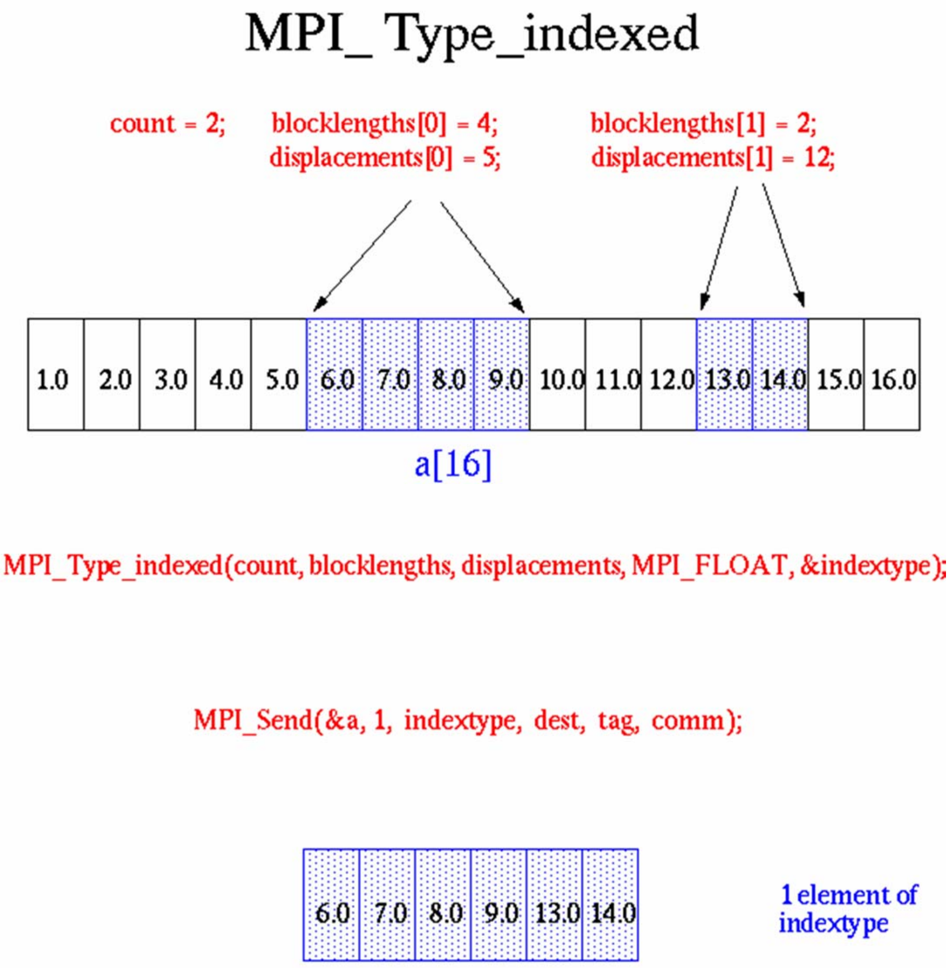
1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10.0 11.0 12.0 13.0 14.0 15.0 16.0

Creates a new datatype *indextype*

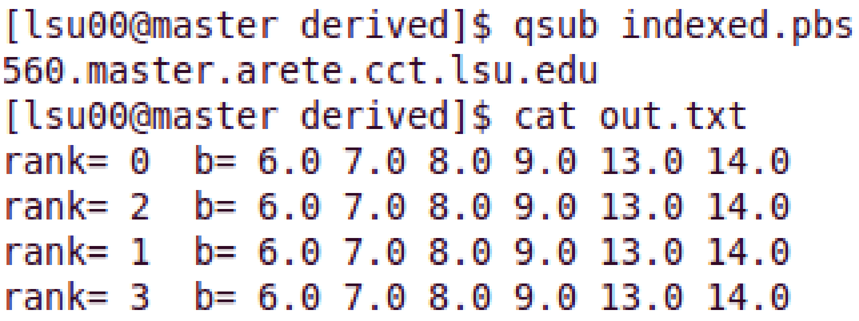
```
    MPI_Isend(a, 1, indextype, i, tag,
MPI_COMM_WORLD, &req);
 }

MPI_Recv(b, NELEMENTS, MPI_FLOAT, source,
tag, MPI_COMM_WORLD, &stat);
printf("rank= %d  b= %3.1f %3.1f %3.1f %3.1f %3.1f %3.1f\n",
   rank,b[0],b[1],b[2],b[3],b[4],b[5]);

MPI_Type_free(&indextype);
MPI_Finalize();
}
```

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatypes - Indexed



```
MPI_Type_indexed(count, blocklengths, displacements, MPI_FLOAT, &indextype);

MPI_Send(&a, 1, indextype, dest, tag, comm);
```



```
[lsu00@master derived]$ qsub indexed.pbs
560.master.arete.cct.lsu.edu
[lsu00@master derived]$ cat out.txt
rank= 0  b= 6.0 7.0 8.0 9.0 13.0 14.0
rank= 2  b= 6.0 7.0 8.0 9.0 13.0 14.0
rank= 1  b= 6.0 7.0 8.0 9.0 13.0 14.0
rank= 3  b= 6.0 7.0 8.0 9.0 13.0 14.0
```

https://computing.llnl.gov/tutorials/mpi/

Topics

- MPI Collective Calls: Synchronization Primitives
- MPI Collective Calls: Communication Primitives
- MPI Collective Calls: Reduction Primitives
- Derived Datatypes: Introduction
- Derived Datatypes: Contiguous
- Derived Datatypes: Vector
- Derived Datatypes: Indexed
- Derived Datatypes: Struct
- Matrix-Vector multiplication : A Case Study
- MPI Profiling calls
- Additional Topics
- Summary

Derived Datatypes : struct

Function: MPI_Type_struct()

```
int MPI_Type_struct(
        int count,
        int *array_of_blocklengths,
        MPI_Aint *array_of_displacements,
        MPI_Datatype *array_of_types,
        MPI_datatype *newtype);
```

Deprecated since MPI-2.0
Removed since MPI-3.0
Replacement: MPI_Type_create_struct

Description:

Returns a new datatype that represents count blocks. Each is defined by an entry in array_of_blocklengths, array_of_displacements and array_of_types. Displacements are expressed in bytes. *count* is an integer that specifies the number of blocks (number of entries in arrays. The *array_of_blocklengths* is the number of elements in each blocks & *array_of_displacements* specifies the byte displacement of each block. The *array_of_types* parameter comprising each block is made of concatenation of type *array_of_types*.

```
...
MPI_Type_struct(2, blockcounts, offsets, oldtypes, &particletype);
...
```

https://computing.llnl.gov/tutorials/mpi/man/MPI_Type_struct.txt

Example : Derived Datatype - struct

```
#include "mpi.h"
#include <stdio.h>
#define NELEM 25
int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, source=0, dest, tag=1, i;
typedef struct {
  float x, y, z;
  float velocity;
  int  n, type;
  }          Particle;
Particle     p[NELEM], particles[NELEM];
MPI_Datatype particletype, oldtypes[2];
int          blockcounts[2];
MPI_Aint     offsets[2];

/* MPI_Aint type used to be consistent with syntax of */
/* MPI_Type_get_extent routine */
MPI_Aint  lb, float_extent;

MPI_Status stat;

MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);

MPI_Type_get_extent(MPI_FLOAT, &lb, &float_extent);
```

```
blockcounts[0] = 4; blockcounts[1] = 2;
offsets[0] = 0; offsets[1] = 4 * float_extent;
oldtypes[0] = MPI_FLOAT; oldtypes[1] = MPI_INT;
MPI_Type_create_struct(2, blockcounts, offsets, oldtypes,
&particletype);
MPI_Type_commit(&particletype);

if (rank == 0) {
  for (i=0; i<NELEM; i++) {
      particles[i].x = i * 1.0;
      particles[i].y = i * -1.0;
      particles[i].z = i * 1.0;
      particles[i].velocity = 0.25;
      particles[i].n = i;
      particles[i].type = i % 2;
     }
  for (i=0; i<numtasks; i++)
     MPI_Send(particles, NELEM, particletype, i, tag, MPI_COMM_WORLD);
}
MPI_Recv(p, NELEM, particletype, source, tag, MPI_COMM_WORLD, &stat);
printf("rank= %d   %3.2f %3.2f %3.2f %3.2f %d %d\n", rank,p[3].x,
     p[3].y,p[3].z,p[3].velocity,p[3].n,p[3].type);

MPI_Type_free(&particletype);
MPI_Finalize();
}
```

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatype - struct

```
#include "mpi.h"
#include <stdio.h>
#define NELEM 25
int main(argc,argv)
int argc;
char *argv[];  {
int numtasks, rank, source=0, dest, tag=1, i;
typedef struct {
  float x, y, z;
  float velocity;
  int  n, type;
  }         Particle;
Particle     p[NELEM], particles[NELEN
MPI_Datatype particletype, oldtypes
int         blockcounts[2];
MPI_Aint    offsets[2];

/* MPI_Aint type used to be consistent with syntax of */
/* MPI_Type_get_extent routine */
MPI_Aint  lb, float_extent;

MPI_Status stat;

MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);

MPI_Type_get_extent(MPI_FLOAT, &lb, &float_extent);
```

Declaring the structure of the heterogeneous datatype
Float, Float, Float, Float, Int, Int

```
blockcounts[0] = 4; blockcounts[1] = 2;
offsets[0] = 0; offsets[1] = 4 * float_extent;
oldtypes[0] = MPI_FLOAT; oldtypes[1] = MPI_INT;
MPI_Type_create_struct(2, blockcounts, offsets, oldtypes,
&particletype);
MPI_Type_commit(&particletype);

if (rank == 0) {
  for (i=0; i<NELEM; i++) {
     particles[i].x = i * 1.0;
     particles[i].y = i * -1.0;
     particles[i].z = i * 1.0;
     particles[i].velocity = (
     particles[i].n = i;
     particles[i].type = i % 2;
     }
  for (i=0; i<numtasks; i++)
     MPI_Send(particles, NELEM,
}
MPI_Recv(p, NELEM, particletyp                                  );
printf("rank= %d   %3.2f %3.2f %
     p[3].y,p[3].z,p[3].velocity,p[3

MPI_Type_free(&particletype);
MPI_Finalize();
}
```

Construct the heterogeneous datatype as an MPI datatype using Struct

Populate the heterogenous MPI datatype with heterogeneous data

https://computing.llnl.gov/tutorials/mpi/

Example : Derived Datatype - struct

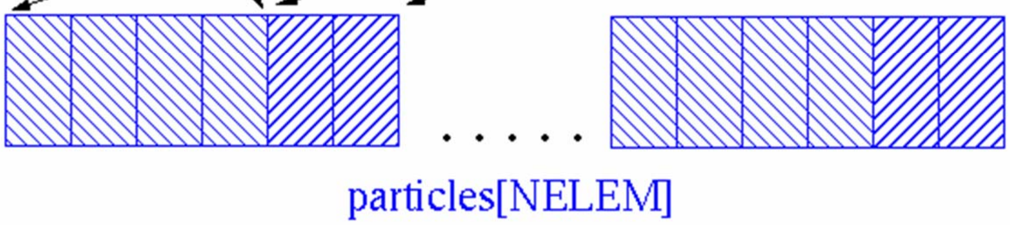
MPI_ Type_struct

typedef struct { float x, y, z, velocity; int n, type; } Particle;
Particle particles[NELEM];

MPI_Type_extent(MPI_FLOAT, &extent);

count = 2; oldtypes[0] = MPI_FLOAT;
offsets[0] = 0;
blockcounts[0] = 4;

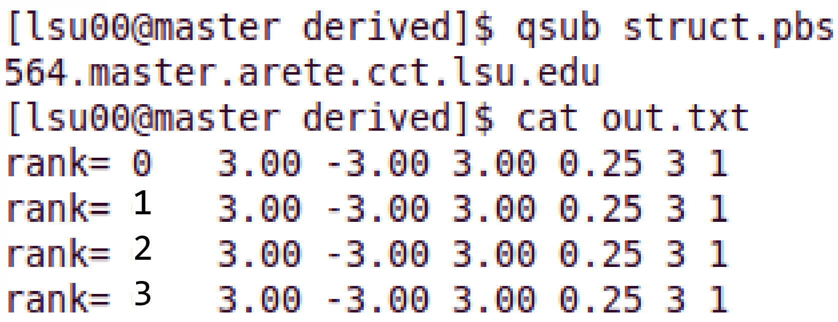
oldtypes[1] = MPI_INT
offsets[1] = 4 * extent;
blockcounts[1] = 2;



MPI_Type_struct(count, blockcounts, offsets, oldtypes, &particletype);

MPI_Send(particles, NELEM, particletype, dest, tag, comm);

Sends entire (NELEM) array of particles, each particle being comprised four floats and two integers.



```
[lsu00@master derived]$ qsub struct.pbs
564.master.arete.cct.lsu.edu
[lsu00@master derived]$ cat out.txt
rank= 0   3.00 -3.00 3.00 0.25 3 1
rank= 1   3.00 -3.00 3.00 0.25 3 1
rank= 2   3.00 -3.00 3.00 0.25 3 1
rank= 3   3.00 -3.00 3.00 0.25 3 1
```

https://computing.llnl.gov/tutorials/mpi/

Topics

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- MPI Collective Calls: Communication Primitives
- MPI Collective Calls: Reduction Primitives
- Derived Datatypes: Introduction
- Derived Datatypes: Contiguous
- Derived Datatypes: Vector
- Derived Datatypes: Indexed
- Derived Datatypes: Struct
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Matrix Vector Multiplication

$$\begin{array}{cc} & \text{Column} \longrightarrow \\ \text{Row} \downarrow & \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,m-2} & a_{0,m-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,m-2} & a_{1,m-1} \\ \vdots & \vdots & & \vdots & \vdots \\ a_{n-2,0} & a_{n-2,1} & \cdots & a_{n-2,m-2} & a_{n-2,m-1} \\ a_{n-1,0} & a_{n-1,1} & \cdots & a_{n-1,m-2} & a_{n-1,m-1} \end{bmatrix} \end{array}$$

Matrix Vector Multiplication

Multiplication of a matrix, **A** and a vector **B**, produces the vector **C** whose elements, *ci* (0 <= *i* < *n*), are computed as follows:

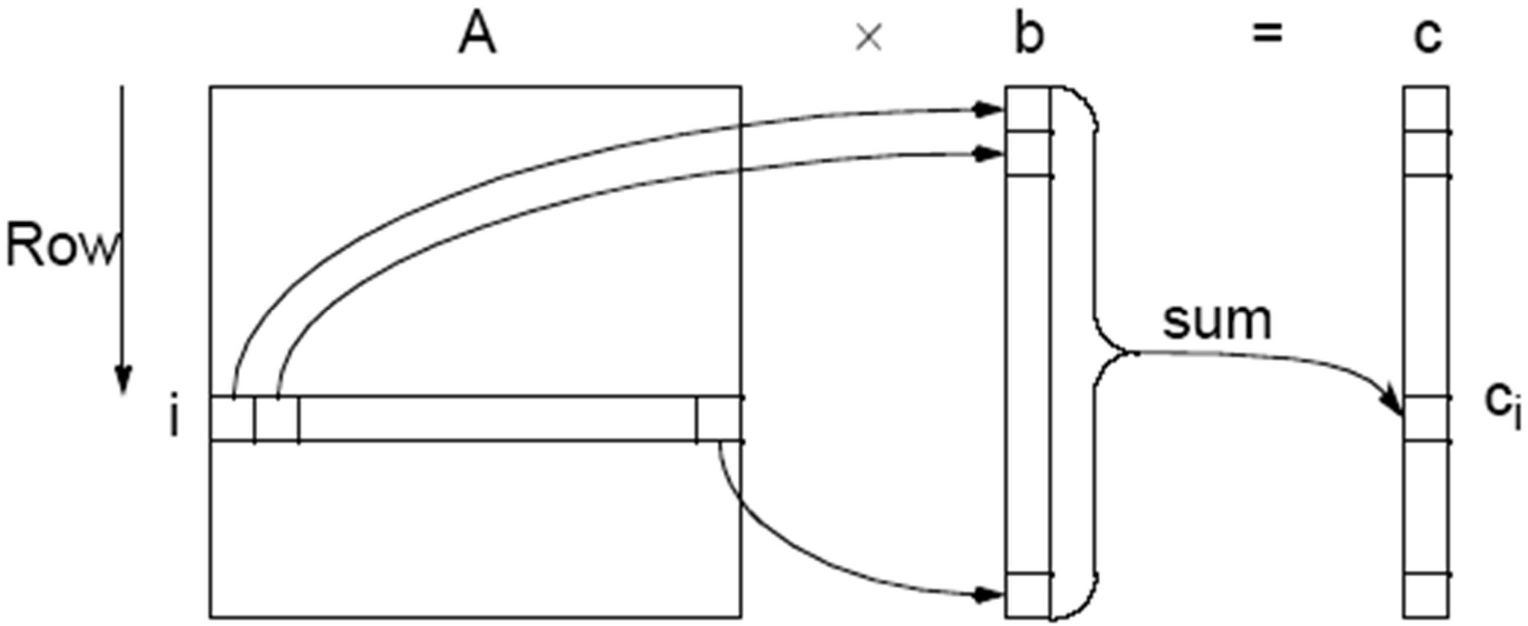
$$C_i = \sum_{k=0}^{k=m} A_{ik} * B_k$$

where **A** is an *n* x *m* matrix and **B** is a vector of size m and C is a vector of size n.

Slides for Parallel Programming Techniques & Applications Using Networked Workstations & Parallel Computers 2nd ed., by B. Wilkinson & M. Allen,

Matrix-Vector Multiplication

c = A x b



Example: Matrix-Vector Multiplication

```
#include "mpi.h"
#include <stdio.h>
#include <stdlib.h>

#define NRA 4              /* number of rows in matrix A */
#define NCA 4              /* number of columns in matrix A */
#define NCB 1              /* number of columns in matrix B */
#define MASTER 0           /* taskid of first task */
#define FROM_MASTER 1         /* setting a message type */
#define FROM_WORKER 2         /* setting a message type */

int main (int argc, char *argv[])
{
int             numtasks,          /* number of tasks in partition */
                taskid,            /* a task identifier */
                numworkers,        /* number of worker tasks */
                source,            /* task id of message source */
                dest,              /* task id of message destination */
                mtype,             /* message type */
                rows,              /* rows of matrix A sent to each worker */
                averow, extra, offset, /* used to determine rows sent to each worker */
                i, j, k, rc;       /* misc */
```

Define the dimensions of the Matrix a([4][4]) and Vector b([4][1])

Example: Matrix-Vector Multiplication

```
double        a[NRA][NCA],        /* Matrix A to be multiplied */
              b[NCA][NCB],        /* Vector B to be multiplied */
              c[NRA][NCB];        /* result Vector C */
MPI_Status status;

MPI_Init(&argc,&argv);
MPI_Comm_rank(MPI_COMM_WORLD,&taskid);
MPI_Comm_size(MPI_COMM_WORLD,&numtasks);
if (numtasks < 2 ) {
  printf("Need at least two MPI tasks. Quitting...\n");
  MPI_Abort(MPI_COMM_WORLD, rc);
  exit(1);
  }
numworkers = numtasks-1;
/*************************** master task ***************
   if (taskid == MASTER)
   {
      printf("mpi_mm has started with %d tasks.\n",numtasks);
      printf("Initializing arrays...\n");
      for (i=0; i<NRA; i++)
         for (j=0; j<NCA; j++)
            a[i][j]= i+j;
      for (i=0; i<NCA; i++)
         for (j=0; j<NCB; j++)
            b[i][j]= (i+1)*(j+1);
```

Declare the matrix , vector to be multiplied and the resultant vector

```
MASTER Initializes the Matrix A  :
  0.00    1.00    2.00    3.00
  1.00    2.00    3.00    4.00
  2.00    3.00    4.00    5.00
  3.00    4.00    5.00    6.00
```

```
MASTER Initializes B :
  1.00
  2.00
  3.00
  4.00
```

Example: Matrix-Vector Multiplication

```
for (i=0; i<NRA; i++)
 {
   printf("\n");
   for (j=0; j<NCA; j++)
     printf("%6.2f   ", a[i][j]);
 }
for (i=0; i<NRA; i++)
 {
   printf("\n");
   for (j=0; j<NCB; j++)
     printf("%6.2f   ", b[i][j]);
 }
/* Send matrix data to the worker tasks */
 averow = NRA/numworkers;
 extra = NRA%numworkers;
 offset = 0;
 mtype = FROM_MASTER;
 for (dest=1; dest<=numworkers; dest++)
 {
   rows = (dest <= extra) ? averow+1 : averow;
    printf("Sending %d rows to task %d offset=%d\n",rows,dest,offset);
    MPI_Send(&offset, 1, MPI_INT, dest, mtype, MPI_COMM_WORLD);
    MPI_Send(&rows, 1, MPI_INT, dest, mtype, MPI_COMM_WORLD);
    MPI_Send(&a[offset][0], rows*NCA, MPI_DOUBLE, dest, mtype,
            MPI_COMM_WORLD);
    MPI_Send(&b, NCA*NCB, MPI_DOUBLE, dest, mtype, MPI_COMM_WORLD);
   offset = offset + rows;
 }
```

Load Balancing : Dividing the Matrix A based on the number of processors

```
MASTER sends Matrix A to workers :
  PROC[0] :: 0.00    1.00    2.00    3.00
  PROC[1] :: 1.00    2.00    3.00    4.00
  PROC[2] :: 2.00    3.00    4.00    5.00
  PROC[3] :: 3.00    4.00    5.00    6.00
```

```
MASTER Sends Vector B to Workers:
  PROC[0] :: 1.00    2.00    3.00    4.00
  PROC[1] :: 1.00    2.00    3.00    4.00
  PROC[2] :: 1.00    2.00    3.00    4.00
  PROC[3] :: 1.00    2.00    3.00    4.00
```

Example: Matrix-Vector Multiplication

```
/* Receive results from worker tasks */
    mtype = FROM_WORKER;
    for (i=1; i<=numworkers; i++)
    {
      source = i;
       MPI_Recv(&offset, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
       MPI_Recv(&rows, 1, MPI_INT, source, mtype, MPI_COMM_WORLD, &status);
       MPI_Recv(&c[offset][0], rows*NCB, MPI_DOUBLE, source, mtype,
               MPI_COMM_WORLD, &status);
      printf("Received results from task %d\n",source);
    }

    /* Print results */
    printf("**************************************************
    printf("Result Matrix:\n");
    for (i=0; i<NRA; i++)
    {
      printf("\n");
      for (j=0; j<NCB; j++)
        printf("%6.2f   ", c[i][j]);
    }
    printf("\n************************************************************\n");
    printf ("Done.\n");
  }
```

The Master process gathers the results and populates the result matrix in the correct order (easily done in this case because matrix index *I* is used to indicate position in result array)

Example: Matrix-Vector Multiplication

```
/**************************** worker task ************
  if (taskid > MASTER)
  {
    mtype = FROM_MASTER;
     MPI_Recv(&offset, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD, &status);
     MPI_Recv(&rows, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD, &status);
     MPI_Recv(&a, rows*NCA, MPI_DOUBLE, MASTER, mtype, MPI_COMM_WORLD, &status);
     MPI_Recv(&b, NCA*NCB, MPI_DOUBLE, MASTER, mtype, MPI_COMM_WORLD, &status);

    for (k=0; k<NCB; k++)
      for (i=0; i<rows; i++)
      {
        c[i][k] = 0.0;
        for (j=0; j<NCA; j++)
            c[i][k] = c[i][k] + a[i][j] * b[j][k];
      }
    mtype = FROM_WORKER;
    MPI_Send(&offset, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD);
    MPI_Send(&rows, 1, MPI_INT, MASTER, mtype, MPI_COMM_WORLD);
    MPI_Send(&c, rows*NCB, MPI_DOUBLE, MASTER, mtype, MPI_COMM_WORLD);
  }
  MPI_Finalize();
}
```

Worker Processes receive workload

```
Proc[1]  A : 1.00    2.00    3.00    4.00
Proc[1]  B : 1.00    2.00    3.00    4.00
```

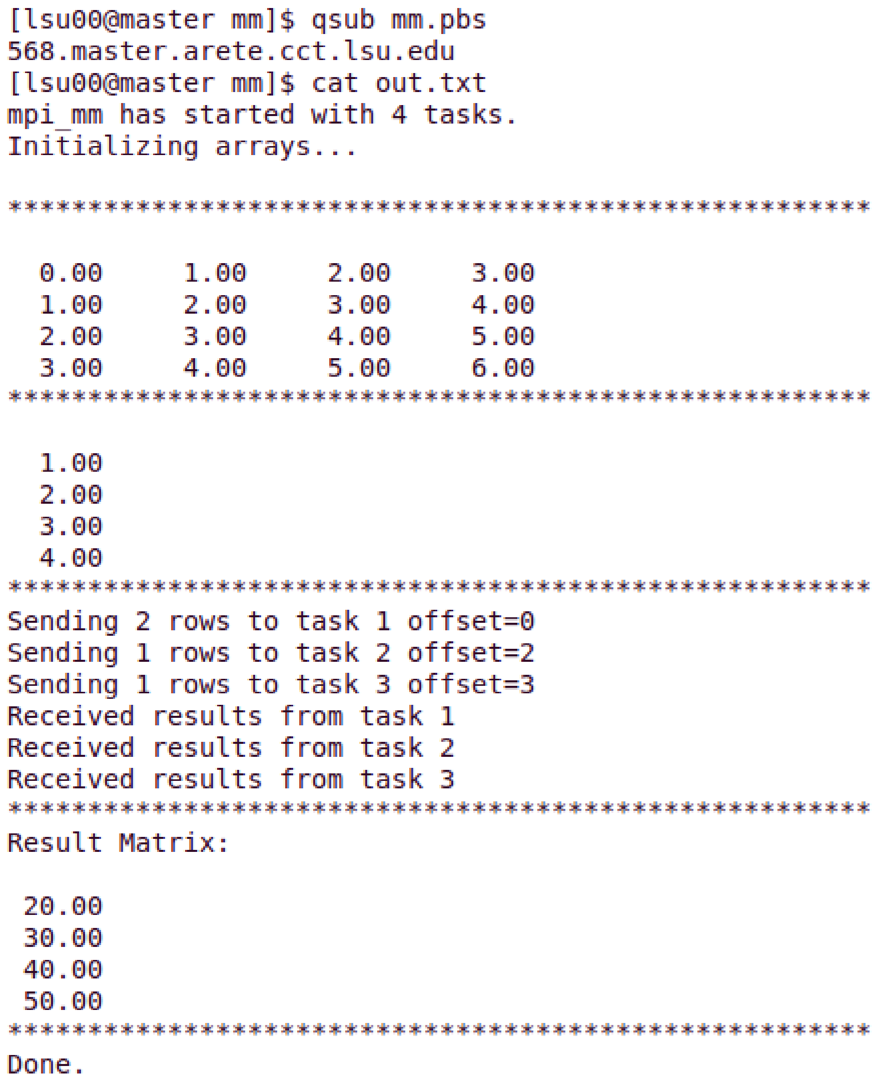
Calculate Result

Proc[1] C: 1.00 + 4.00 + 9.00 + 16.00

Worker sends result to MASTER

Proc[1] C : 20.00

Example: Matrix-Vector Multiplication (Results)



```
[lsu00@master mm]$ qsub mm.pbs
568.master.arete.cct.lsu.edu
[lsu00@master mm]$ cat out.txt
mpi_mm has started with 4 tasks.
Initializing arrays...

******************************************************

  0.00     1.00     2.00     3.00
  1.00     2.00     3.00     4.00
  2.00     3.00     4.00     5.00
  3.00     4.00     5.00     6.00
******************************************************

  1.00
  2.00
  3.00
  4.00
******************************************************
Sending 2 rows to task 1 offset=0
Sending 1 rows to task 2 offset=2
Sending 1 rows to task 3 offset=3
Received results from task 1
Received results from task 2
Received results from task 3
******************************************************
Result Matrix:

 20.00
 30.00
 40.00
 50.00
******************************************************
Done.
```

Topics

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- MPI Collective Calls: Communication Primitives
- MPI Collective Calls: Reduction Primitives
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MPI Profiling : MPI_Wtime

Function: MPI_Wtime()

```
double MPI_Wtime()
```

Description:

Returns time in seconds elapsed on the calling processor. Resolution of time scale is determined by the MPI environment variable MPI_WTICK. When the MPI environment variable MPI_WTIME_IS_GLOBAL is defined and set to true, the the value of MPI_Wtime is synchronized across all processes in MPI_COMM_WORLD

```
 double time0;
...
 time0 = MPI_Wtime();
...
 printf("Hello From Worker #%d %lf \n", rank, (MPI_Wtime() – time0));
```

http://www-unix.mcs.anl.gov/mpi/www/www3/MPI_Wtime.html

Timing Example: MPI_Wtime

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

main(int argc, char **argv)
{
  int size, rank;
  double time0, time1;
  MPI_Init(&argc, &argv);
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
  MPI_Comm_size(MPI_COMM_WORLD, &size);

  time0 = MPI_Wtime();

  if(rank==0)
    {
      printf(" Hello From Proc0 Time = %lf \n", (MPI_Wtime() – time0));
    }
  else
    {
      printf("Hello From Worker #%d %lf \n", rank, (MPI_Wtime() – time0));
    }
  MPI_Finalize();
}
```

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Potential Pitfall

- We need to be sure that every receive has a matching send
  - Suppose process q calls
    - MPI_Send(send_buf_p, send_buf_sz, send_type, dest, send_tag, send_comm);
  - And process r calls
    - MPI_Recv(recv_buf_p, recv_buf_sz, recv_type, src, recv tag, recv_comm, &status);
  - The message sent by q with the above call to MPI_Send can be received by r with the call to MPI_Recv if:
    - recv_comm = send_comm,
    - recv_tag = send_tag,
    - dest = r, and
    - src = q

Wildcard Arguments

- MPI_ANY_SOURCE
- MPI_ANY_TAG
- Only a receiver can use a wildcard argument. Senders must specify a process ran and a nonnegative tag

- Example:
  - If process 0 executes the following code, it can receive the results in the order in which the processes finish:

```
for (i = 1; i < comm_sz; i++) {
   MPI_Recv(result, result_sz, result_type, MPI_ANY_SOURCE,
         result_tag, comm, MPI_STATUS_IGNORE);
   Process_result(result);
}
```

Input/Ouput

- Although the MPI standard doesn’t specify which processes have access to which I/O devices, virtually all MPI implementations allow *all* the processes in MPI_COMM_WORLD full access to stdout and stderr
  - so most MPI implementations allow all processes to execute printf and fprintf(stderr, ...)
- Unlike output, most MPI implementations only allow process 0 in MPI_COMM_WORLD access to stdin
  - This makes sense: If multiple processes have access to stdin, which process should get which parts of the input data?

Collective vs. Point-to-point Communications

- All the processes in the communicator must call the same collective function
  - For example, a program that attempts to match a call to MPI_Reduce on one process with a call to MPI_Recv on another process is erroneous, and, in all likelihood, the program will hang or crash.
- The arguments passed by each process to an MPI collective communication must be “compatible.”
  - For example, if one process passes in 0 as the dest process and another passes in 1, then the outcome of a call to MPI_Reduce is erroneous, and, once again, the program is likely to hang or crash.
- Collective communications don’t use tags

Collective vs. Point-to-point Communications (Cont’d)

- The names of the memory locations are irrelevant to the matching, of the calls to MPI_Reduce
  - The order of the calls will determine the matching
  - For example, Suppose that each process calls MPI_Reduce with operator MPI_SUM, and destination process 0
    - The value stored in b will be 1 + 2 + 1 = 4
    - The value stored in d will be 2 + 1 + 2 = 5

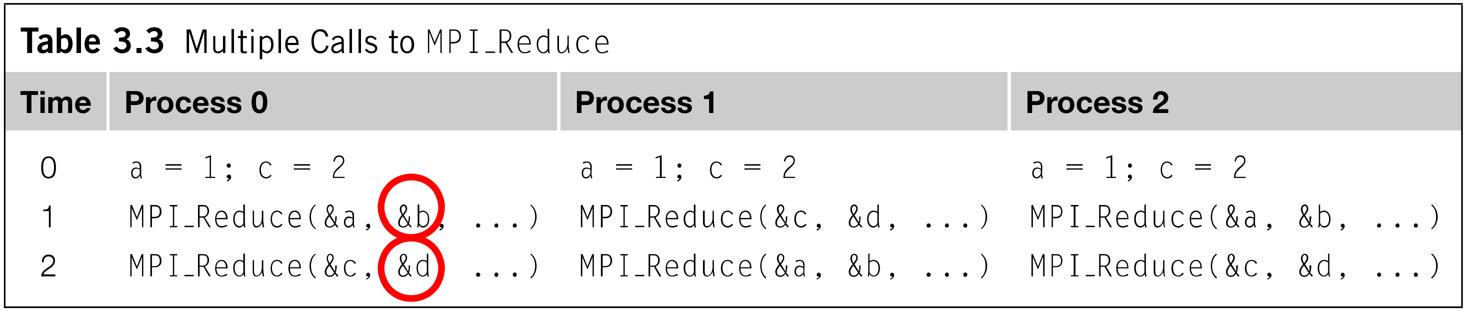

Table 3.3 Multiple Calls to `MPI_Reduce`

Time	Process 0	Process 1	Process 2
0	`a = 1; c = 2`	`a = 1; c = 2`	`a = 1; c = 2`
1	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`
2	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`

MPI topics we did Not Cover

- Topologies: map a communicator onto, say, a 3D Cartesian processor grid
  - Implementation can provide ideal logical to physical mapping
- Rich set of I/O functions: individual, collective, blocking and non-blocking
  - Collective I/O can lead to many small requests being merged for more efficient I/O
- One-sided communication: puts and gets with various synchronization schemes
  - Implementations not well-optimized and rarely used
  - Redesign of interface is underway
- Task creation and destruction: change number of tasks during a run
  - Few implementations available

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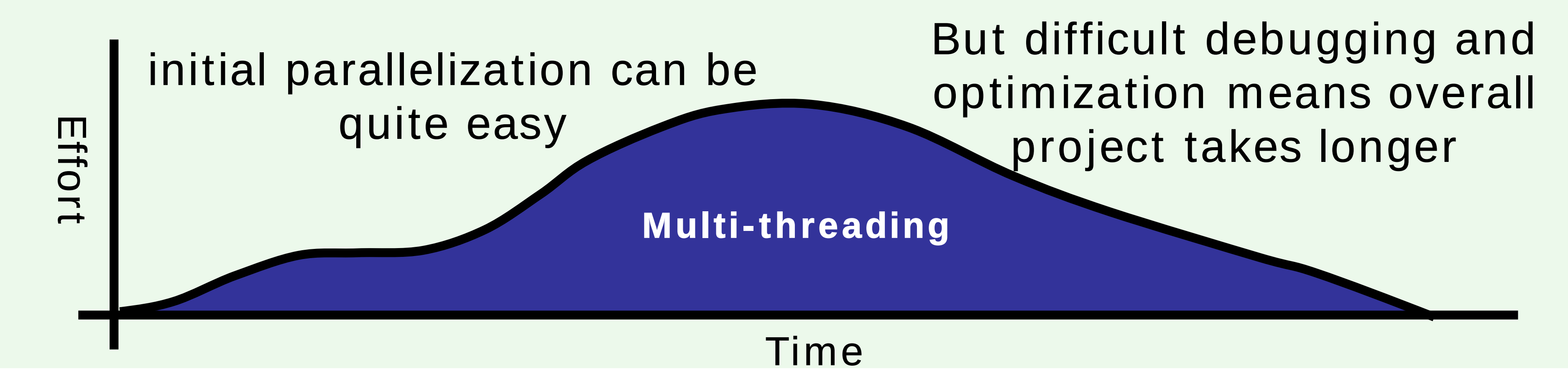
MPI isn’t as hard as many believe

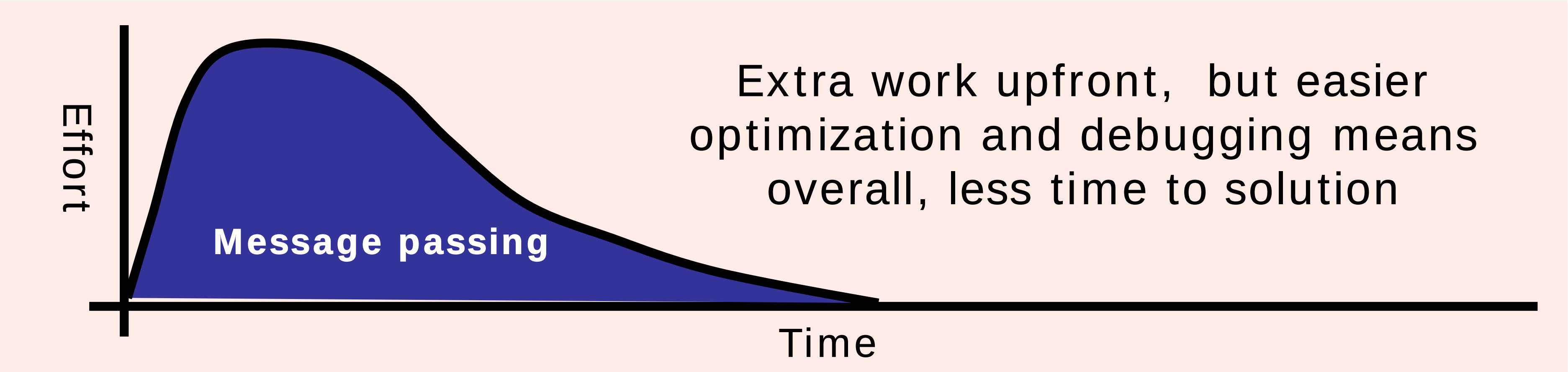
- There are over 330 functions in the MPI spec, but most programs only use a small subset:
  - Startup
    - MPI_Init, MPI_Finalize
  - Information on the processes
    - MPI_Comm_rank, MPI_Comm_size,
  - Point-to-point communication
    - MPI_Irecv, MPI_Isend, MPI_Wait, MPI_Send, MPI_Recv
  - Collective communication
    - MPI_Reduce, MPI_Allreduce, MPI_Bcast, MPI_Allgather

Multithreading vs Message Passing



Proving that a shared address space program using semaphores is race free is an NP-complete problem

P. N. Klein, H. Lu, and R. H. B. Netzer, Detecting Race Conditions in Parallel Programs that Use Semaphores, Algorithmica, vol. 35 pp. 321–345, 2003



Source: Tim Mattson, "Recent developments in parallel programming: the good, the bad, and the ugly", Euro-Par 2013