

MPI and Collective Communication Patterns

Chris Kauffman

*Last Updated:
Tue Feb 7 02:00:51 PM CST 2023*

Logistics

Reading: Grama Ch 6 + 4

- ▶ Ch 6: MPI basics
- ▶ Ch 4: Communication patterns

Assignments

A2 will go up soon, feature MPI Coding

Today

- ▶ More MPI programming
- ▶ Discuss Comm. Patterns

Thursday Lecture + Mini Exam 1

- ▶ 45-min lecture
- ▶ 30-min Mini-Exam 1

Beginning or End of Lecture??

Exercise: MPI Basics Review

- ▶ What are the two basic operations required for distributed memory parallel programming?
- ▶ Describe some variants for these operations.
- ▶ What is a very common library for doing distributed parallel programming?
- ▶ How do the two main operations look in that library?
- ▶ How does one compile/run programs with this library?

Answers: MPI Basics Review

- ▶ `send(data,count,dest)` and `receive(data,count,source)` are the two essential ops for distributed parallel programming
- ▶ `send/receive` can be
 - ▶ blocking: wait for the partner to link up and complete the transaction
 - ▶ non-blocking: don't wait now but check later to before using/changing the message data
 - ▶ buffered: a special area of memory is used to facilitate the sends more efficiently
- ▶ MPI: The Message Passing Interface, common distributed memory programming library
- ▶ Send and Receive in MPI

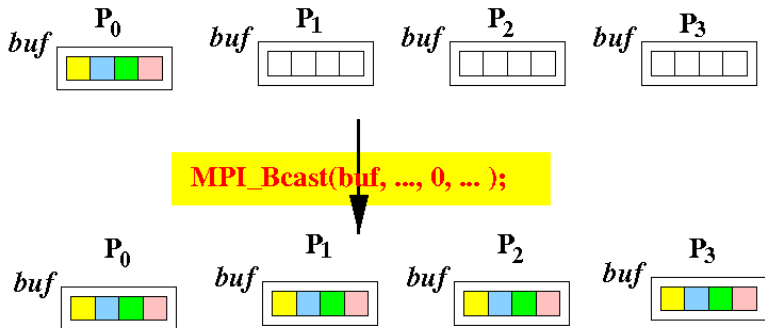
```
MPI_Send(buf, len, MPI_INT, dest, MPI_COMM_WORLD);
MPI_Recv(buf, len, MPI_INT, source, MPI_COMM_WORLD,
          MPI_STATUS_IGNORE);
```
- ▶ Compile/Run

```
mpicc -o prog parallel-program.c
mpirun -np 8 prog
```

Patterns of Communication

- ▶ Common patterns exist in many algorithms
- ▶ Reasoning about algorithms easier if these are “primitives”
 - ▶ “I’ll broadcast to all procs here and gather all results here”
vs
“I’ll use a loop here to send this data to every processor and a loop here for every processor to send its data to proc 0 which needs all of it.”
- ▶ MPI provides a variety of collective communication operations which make these single function calls
- ▶ Vendors of super-computers usually implement those functions to run as quickly as possible on the network provided - repeated halving/double if the network matches
- ▶ By making the function call, you get all the benefit the network can provide in terms of speed

Broadcasting One-to-All



Source: Shun Yan Cheung Notes on MPI

- ▶ Root processor wants to transmit data buffer to all processors
- ▶ Broadcast distributes to all procs
- ▶ Each proc gets same stuff in data buffer

Broadcast Example Code

In broadcast_demo.c

```
// Everyone allocates
```

```
data = (int*)malloc(sizeof(int) * num_elements);
```

```
// Root fills data by reading from file/computation
```

```
if(procid == root_proc){
```

```
    for(i=0; i<num_elements; i++){
```

```
        data[i] = i*i;
```

```
    }
```

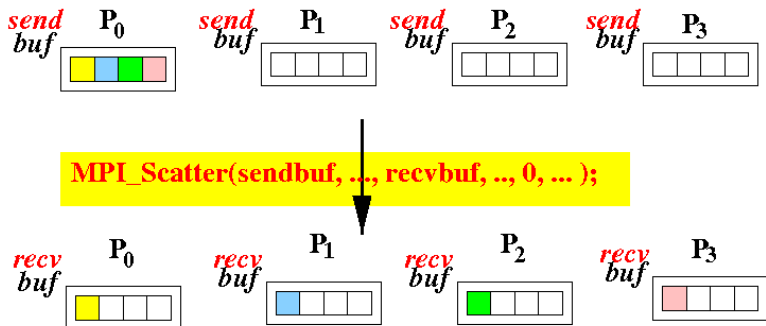
```
}
```

```
// Everyone calls broadcast, root proc sends, others receive
```

```
MPI_Bcast(data, num_elements, MPI_INT, root_proc,  
          MPI_COMM_WORLD);
```

```
// data[] now filled with same portion of root_data[] on each proc
```

Scatter from One To All



Source: Shun Yan Cheung Notes on MPI

- ▶ Root processor has slice of data for each proc
- ▶ Scatter distributes to each proc
- ▶ Each proc gets an individualized message

Scatter Example

In scatter_demo.c

```
// Root allocates/fills root_data by reading from file/computation
if(procid == root_proc){
    root_data = malloc(sizeof(int) * total_elements);
    for(i=0; i<total_elements; i++){
        root_data[i] = i*i;
    }
}

// Everyone allocates for their share of data including root
data = malloc(sizeof(int) * elements_per_proc);

// Everyone calls scatter, root proc sends, others receive
MPI_Scatter(root_data, elements_per_proc, MPI_INT,
            data, elements_per_proc, MPI_INT,
            root_proc, MPI_COMM_WORLD);
// data[] now filled with unique portion from root_data[]
```

Exercise: Scatter a Matrix

Often have Matrix and Vector data in HPC / Parallel Computing

```
// mat vec multiply
double **mat = ...;
...;
mat[i][j] = ...;
double *vec = ...;
double *out = ...;
for(int i=0; i<rows; i++){
    for(int j=0; j<cols; j++){
        out[i] = mat[i][j]*vec[j];
    }
}
```

- ▶ How can one MPI_Scatter() the rows of a matrix?
- ▶ What assumptions must be true about the matrix data?

Answers: Scatter a Matrix

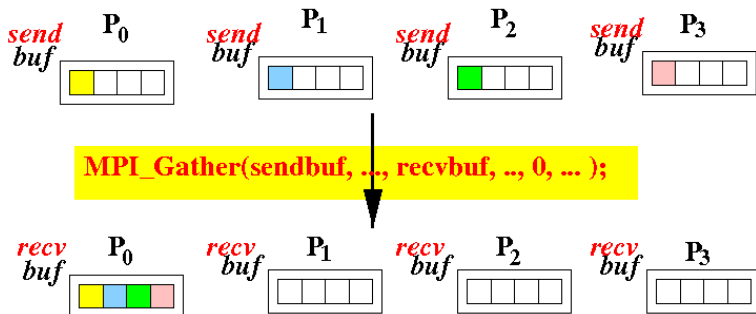
- ▶ Typically matrix must be allocated in **one block of memory** - single malloc()
- ▶ Allows a single MPI_Scatter() to scatter groups of rows

```
{  
    // allocate data for all of matrix  
    double *all = malloc(rows*cols * sizeof(double));  
  
    // allocate / assign row pointers within single block  
    double **mat = malloc(rows * sizeof(double*));  
    for(int i=0; i<rows; i++){  
        mat[i] = &all[i*cols];  
    }  
  
    mat[i][j] = 5.5;           // assign via row pointer  
}
```

Answers: Scatter a Matrix

```
{  
    double *all = NULL;  
  
    // root reads in matrix rows  
    if(rank == root_proc){  
        all = malloc(rows*cols * sizeof(double));  
        fread(all, sizeof(double), rows*cols, infile);  
    }  
  
    // set up and perform scatter  
    int rows_per_proc = rows / nprocs;  
    int elems_per_proc = rows_per_proc * cols;  
    double *myrows = malloc(sizeof(double) * elems_per_proc);  
    MPI_Scatter(all,      elements_per_proc, MPI_INT,  
                myrows, elements_per_proc, MPI_INT,  
                root_proc, MPI_COMM_WORLD);  
}
```

Gather from All to One



Source: Shun Yan Cheung Notes on MPI

- ▶ Every processor has data in send buffer
- ▶ Root processor needs all data ordered by `proc_id`
- ▶ Root ends with all data in a receive buffer

Gather Example

```
// gather_demo.c
int total_elements = 16;
int elements_per_proc = total_elements / total_procs;

// Everyone allocates for their share of data including root
data = malloc(sizeof(int) * elements_per_proc);

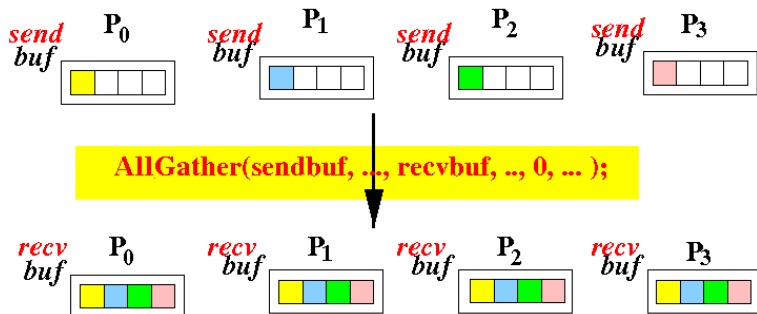
// Each proc fills data[] with "unique" values
int x = 1;
for(i=0; i<elements_per_proc; i++){
    data[i] = x;
    x *= (procid+2);
}
// data[] now filled with unique values on each proc

// Root allocates root_data to be filled with gathered data
if(procid == root_proc){
    root_data = malloc(sizeof(int) * total_elements);
}

// Everyone calls gather, root proc receives, others send
MPI_Gather(data,          elements_per_proc, MPI_INT,
           root_data, elements_per_proc, MPI_INT,
           root_proc, MPI_COMM_WORLD);

// root_data[] now contains each procs data[] in order
```

All Gather: Everyone to Everyone



Source: Shun Yan Cheung Notes on MPI

- ▶ Every processor has data in send buffer
- ▶ **All** processors need all data ordered by `proc_id`
- ▶ All procs end with all data in receive buffer

All-Gather Example

```
// allgather_demo.c
// Everyone allocates for their share of data including root
data = malloc(sizeof(int) * elements_per_proc);

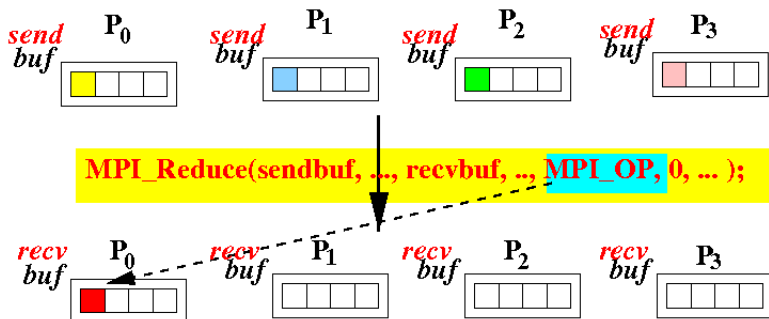
// Each proc fills data[] with "unique" values
int x = 1;
for(i=0; i<elements_per_proc; i++){
    data[i] = x;
    x += (proc_id+2);
}
// data[] now filled with unique values on each proc

// Everyone allocates all_data to be filled with gathered data
all_data = malloc(sizeof(int) * total_elements);

// Everyone calls all-gather, everyone sends and receives
MPI_Allgather(data,      elements_per_proc, MPI_INT,
              all_data, elements_per_proc, MPI_INT,
              MPI_COMM_WORLD);

// all_data[] now contains each procs data[] in order on
// all procs
```


Reduction: All to One



Source: Shun Yan Cheung Notes on MPI

- ▶ Every processor has data in send buffer
- ▶ Root processor needs all data **reduced**
 - ▶ Reduction operation is transitive
 - ▶ Several pre-defined via constants
 - ▶ Common: MPI_MAX, MPI_MIN, MPI_SUM, MPI_PROD
- ▶ Root ends with reduced data in receive buffer

Reduce Example

```
// reduce_demo.c
{ // Each proc fills data[] with unique values
    int x = 1;
    for(i=0; i<total_elements; i++){
        data[i] = x;
        x *= (procid+2);
    }
    // data[] now filled with unique values on each proc

    // Root allocates root_data to be filled with reduced data
    if(procid == root_proc){
        root_data = malloc(sizeof(int) * total_elements);
    }

    // Everyone calls reduce, root proc receives,
    // others send and accumulate
    MPI_Reduce(data, root_data, total_elements, MPI_INT,
                MPI_SUM, // operation to perform on each element
                root_proc, MPI_COMM_WORLD);
    // root_data[] now contains each procs data[] summed up
}
```

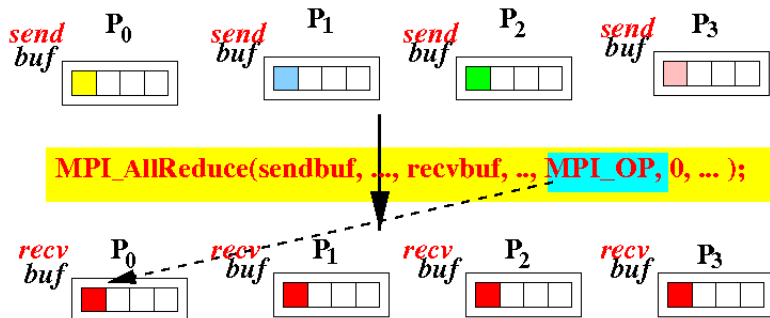
Note: Reduction's Array Argument

- ▶ `MPI_Reduce()` works on a `data[]` argument like others
- ▶ Reduction happens for each element so that

```
root_proc = 0;
MPI_Reduce(data, root_data, total_elements, MPI_INT,
           MPI_SUM, root_proc, MPI_COMM_WORLD);
// results in
P0.root_data[0] = P0.data[0] + P1.data[0] + P2.data[0] + ...
P0.root_data[1] = P0.data[1] + P1.data[1] + P2.data[1] + ...
P0.root_data[2] = P0.data[2] + P1.data[2] + P2.data[2] + ...
...
```

- ▶ To get a single sum, Procs should iterate on their own array
THEN `MPI_Reduce()` on a single vlaue

Reduction for All: All-Reduce



Source: Shun Yan Cheung Notes on MPI

- ▶ Every processor has data in send buffer
- ▶ All processors need all data **reduced**
- ▶ All procs end with reduced data in a receive buffer

Allreduce Example

```
{ // Each proc fills data[] with unique values
  int x = 1;
  for(i=0; i<total_elements; i++){
    data[i] = x;
    x *= (procid+2);
  }
  // data[] now filled with unique values on each proc

  // Everyone allocates reduced_data to be filled with reduced data
  reduced_data = malloc(sizeof(int) * total_elements);

  // Everyone calls reduce, everyone sends and receives
  MPI_Allreduce(data, reduced_data, total_elements, MPI_INT,
                MPI_SUM, // operation to perform on each element
                MPI_COMM_WORLD);
  // reduced_data[] now contains each procs data[] summed up
}
```

In-place Reduction

- ▶ Occasionally want to do reductions in-place: send and receive buffers are the same.
- ▶ May be useful in upcoming assignment
- ▶ Use `MPI_IN_PLACE` for the send buffer

```
{ // Everyone calls reduce, everyone sends and receives
  MPI_Allreduce(MPI_IN_PLACE,    // no destination buffer - use data
                data,            // reduction is placed here
                total_elements, MPI_INT,
                MPI_SUM,          // op to perform on each element
                MPI_COMM_WORLD);
  // data[] now contains each procs data[], min elements
}
```

Summary of Communications

Operation	MPI Function	Synopsis
Individual		
Send	MPI_Send	One-to-one send
Receive	MPI_Recv	One-to-one receive
Send/Receive	MPI_Sendrecv	One-to-one send/receive
Collective		
Barrier	MPI_Barrier	All wait for stragglers
Broadcast	MPI_Bcast	Root to all, all data copied
Scatter	MPI_Scatter	Root to all, slices of data copied
Gather	MPI_Gather	All to root, slices ordered on Root
Reduce	MPI_Reduce	All to root, data reduced on Root
All-Gather	MPI_Allgather	All to all, data ordered
All-Reduce	MPI_Allreduce	All to all, data reduced
Not Discussed		
Prefix	MPI_Prefix	All-to-all, data ordered/reduced
All-to-AllP	MPI_Alltoall	All-to-all, personal messages

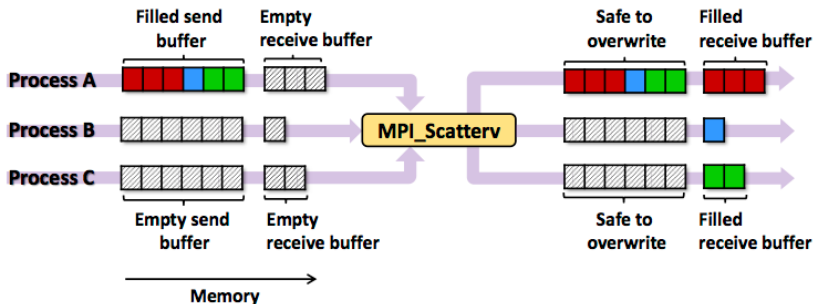
Vector Versions

- ▶ Collective comm ops like `MPI_Scatter` assume same amount of data to/from each processor
- ▶ Not a safe, general assumption (e.g. $\text{len} \% P \neq 0$)
- ▶ *Vector*¹ versions of each comm op exist which relax these assumptions, allow arbitrary data counts per proc
- ▶ Provide additional arguments indicating
 - ▶ `counts`: How many elements each proc has
 - ▶ `displs`: Offsets elements are/will be stored in master array

Operation	Equal counts	Different counts
Broadcast	<code>MPI_Bcast</code>	
Scatter	<code>MPI_Scatter</code>	<code>MPI_Scatterv</code>
Gather	<code>MPI_Gather</code>	<code>MPI_Gatherv</code>
All-Gather	<code>MPI_Allgather</code>	<code>MPI_Allgatherv</code>
Reduce	<code>MPI_Reduce</code>	
All-Reduce	<code>MPI_Allreduce</code>	

¹“Vector” here means extra array arguments, NOT hardware-level parallelism like “Vector Instruction”

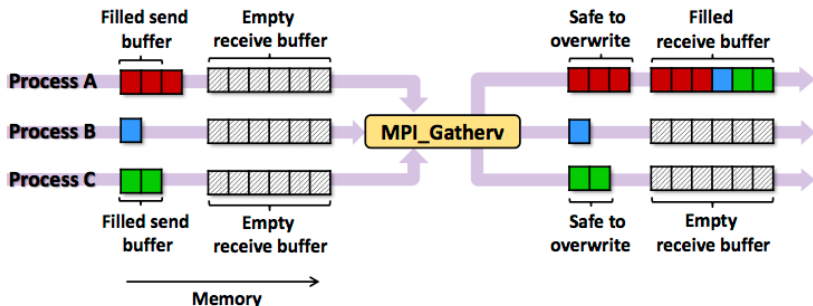
MPI_Scatterv Example



Source: SKIRT Docs

```
//          P0 P1 P2
int counts[] = { 3, 1, 2};
int displs[] = { 0, 3, 4};
//          P0 P0 P0 P1 P2 P2
int send[] = { 10, 20, 30, 40, 50, 60 };
int *recv = malloc(counts[rnk] * sizeof(int));
MPI_Scatterv(send, counts, displs, MPI_INT,
             recv, counts[rnk], MPI_INT,
             0, MPI_COMM_WORLD);
```

MPI_Gatherv Example



Source: SKIRT Docs

```
int total = 6;
int counts[] = { 3, 1, 2};
int displs[] = { 0, 3, 4};
int send[counts[rk]];
int *recv, i;
for(i=0; i<counts[rk]; i++){
    send[i] = rk*(i+1);
}
```

```
recv = (rk!=0) ? NULL :
    malloc(total * sizeof(int));

MPI_Gatherv(
    send, counts[rk], MPI_INT,
    recv, counts, displs, MPI_INT,
    0, MPI_COMM_WORLD);
```

Dynamic Count and Displacements for Vector Comm Ops

- ▶ Common prob: # of procs does not evenly divide data size
- ▶ Use the vector versions of collective ops
- ▶ To calculate counts and displacements and spread work evenly, use a pattern like the below (see `scatterv_demo.c`)

```
int total_elements = 16;
int *counts = malloc(total_procs * sizeof(int));
int *displs = malloc(total_procs * sizeof(int));

// Divide total_elements as evenly as possible: lower numbered
// processors get one extra element each.
int elements_per_proc = total_elements / total_procs;
int surplus           = total_elements % total_procs;
for(i=0; i<total_procs; i++){
    counts[i] = (i < surplus) ? elements_per_proc+1 : elements_per_proc;
    displs[i] = (i == 0) ? 0 : displs[i-1] + counts[i-1];
}
// counts[] and displs[] now contain relevant data for a scatterv,
// gatherv, all-gatherv calls
```

Barriers

```
MPI_Barrier(MPI_COMM_WORLD);
```

- ▶ Causes all processors to synchronize at the given line of code
- ▶ Early arrivers idle while other procs catch up
- ▶ To be avoided if possible as it almost always incurs idle time
- ▶ Unavoidable in some select scenarios
- ▶ Can be useful in debugging to introduce barriers

Basic Debugging Discipline

Q: How do I debug Open MPI processes in parallel?

A: This is a difficult question...

– *[OpenMPI FAQ on Debugging](#)*

- ▶ Commercial Parallel Debuggers exist, TotalView is popular
- ▶ For small-ish programs...
Debug Printing + Valgrind + Effort + Patience
will usually suffice

```
> mpirun -v -np 4 valgrind ./my_program arg1 arg2
```