CS 267
Lecture 10: Advanced MPI and Collective Communication Algorithms

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https://sites.google.com/lbl.gov/cs267-spr2021/

Distributed deep learning is all about collectives

TORCH.DISTRIBUTED

Backends

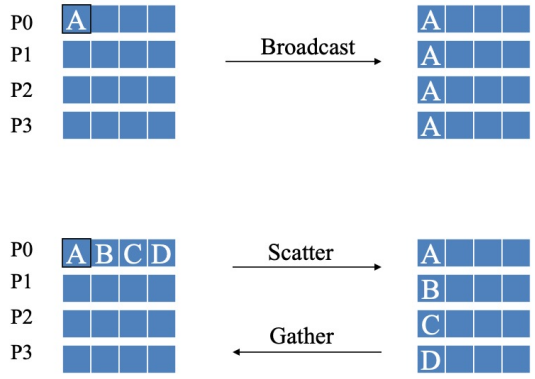
Facebook's gloo: "**Collective** communications library with various primitives for multi-machine training".

`torch.distributed` supports three backends, each with different capabilities. The table below shows which functions are available for use with CPU / CUDA tensors. MPI supports CUDA only if the implementation used to build PyTorch supports it.

Backend	`gloo`		`mpi`		`nccl`	
Device	CPU	GPU	CPU	GPU	CPU	GPU
send	✓	✘	✓	?	✘	✘
recv	✓	✘	✓	?	✘	✘
broadcast	✓	✓	✓	?	✘	✓
all_reduce	✓	✓	✓	?	✘	✓
reduce	✓	✘	✓	?	✘	✓
all_gather	✓	✘	✓	?	✘	✓
gather	✓	✘	✓	?	✘	✘
scatter	✓	✘	✓	?	✘	✘

The NVIDIA **Collective** Communications Library

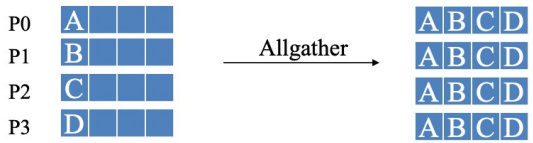
Collective Data Movement

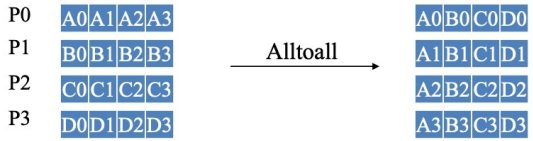


Comments on Broadcast, other Collectives

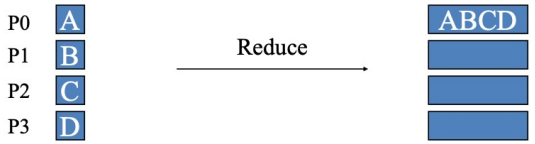
- **All collective operations must be called by *all* processes in the communicator**
- **MPI_Bcast is called by both the sender (called the root process) and the processes that are to receive the broadcast**
  - **"root" argument is the rank of the sender; this tells MPI which process originates the broadcast and which receive**

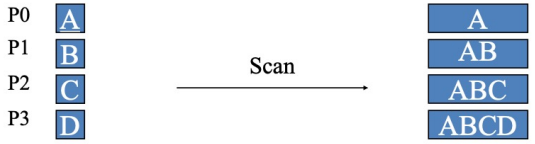
More Collective Data Movement





Collective Computation





MPI Collective Routines

- **Many Routines:** `Allgather`, `Allgatherv`, `Allreduce`, `Alltoall`, `Alltoallv`, `Bcast`, `Gather`, `Gatherv`, `Reduce`, `Reduce_scatter`, `Scan`, `Scatter`, `Scatterv`
- `All` **versions deliver results to all participating processes, not just root.**
- **V versions allow the chunks to have variable sizes.**
- `Allreduce`, `Reduce`, `Reduce_scatter`, **and** `Scan` **take both built-in and user-defined combiner functions.**

MXX: An MPI productivity library for C++11

A few annoying redundancies:

- Any irregular exchange (e.g, alltoallv, allgatherv) is a multi step process: **(1) exchange counts**, (2) copy data to buffer, (3) allocate space, **(4) exchange actual data**
- have to create a derived data type for any non-PDO data
- have to map user defined functions to MPI functions

The MXX way:

```
// lets take some pairs and find the one with the max second element
std::pair<int, double> v = ...;
std::pair<int, double> min_pair = mxx::allreduce(v,
                  [](const std::pair<int, double>& x,
                    const std::pair<int, double>& y){
                     return x.second > y.second ? x : y;
                  });
```

Available at: https://github.com/patflick/mxx

SUMMA Algorithm

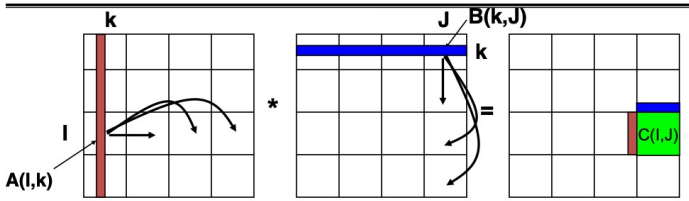
° **SUMMA = Scalable Universal Matrix Multiply**

° **Slightly less efficient than Cannon**
… but simpler and easier to generalize

° **Presentation from van de Geijn and Watts**
- **www.netlib.org/lapack/lawns/lawn96.ps**
- **Similar ideas appeared many times**

° **Used in practice in PBLAS = Parallel BLAS**
- **www.netlib.org/lapack/lawns/lawn100.ps**

SUMMA



- I, J represent all rows, columns owned by a processor
- k is a single row or column
  - or a block of b rows or columns
- C(I,J) = C(I,J) + Σ_k A(I,k)*B(k,J)
- Assume a p_r by p_c processor grid (p_r = p_c = 4 above)
  - Need not be square

MPI_Comm_split

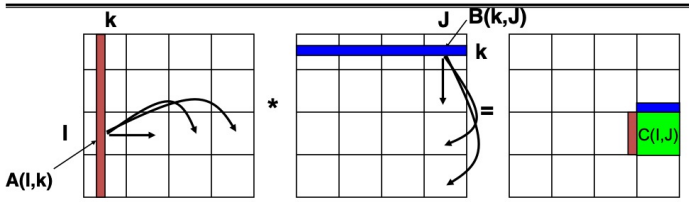
```
int MPI_Comm_split( MPI_Comm comm,
                    int color,
                    int key,
                    MPI_Comm *newcomm)
```

MPI's internal Algorithm:

1. Use MPI_Allgather to get the color and key from each process
2. Count the number of processes with the same color; create a communicator with that many processes. If this process has MPI_UNDEFINED as the color, create a process with a single member.
3. Use key to order the ranks

Color: controls assignment to new communicator
Key: controls rank assignment within new communicator

SUMMA



For k=0 to n-1 … or n/b-1 where b is the block size
… = # cols in A(I,k) and # rows in B(k,J)
  for all I = 1 to p_r … in parallel
    owner of A(I,k) broadcasts it to whole processor row
  for all J = 1 to p_c … in parallel
    owner of B(k,J) broadcasts it to whole processor column
  Receive A(I,k) into Acol
  Receive B(k,J) into Brow
  C(myproc , myproc) = C(myproc , myproc) + Acol * Brow

(naïve) SUMMA in MPI

```
void SUMMA(double *mA, double *mB, double *mc, int p_c)
{
    int row_color = rank / p_c; // p_c = sqrt(p) for simplicity
    MPI_Comm row_comm;
    MPI_Comm_split(MPI_COMM_WORLD, row_color, rank, &row_comm);

    int col_color = rank % p_c;
    MPI_Comm col_comm;
    MPI_Comm_split(MPI_COMM_WORLD, col_color, rank, &col_comm);

    for (int k = 0; k < p_c; ++k) {
        if (col_color == k)  memcpy(Atemp, mA, size);
        if (row_color == k)  memcpy(Btemp, mB, size);

        MPI_Bcast(Atemp, size, MPI_DOUBLE, k, row_comm);
        MPI_Bcast(Btemp, size, MPI_DOUBLE, k, col_comm);

        SimpleDGEMM(Atemp, Btemp, mc, N/p, N/p, N/p);
    }
}
```


MPI Built-in Collective Computation Operations

° MPI_MAX	Maximum
° MPI_MIN	Minimum
° MPI_PROD	Product
° MPI_SUM	Sum
° MPI_LAND	Logical and
° MPI_LOR	Logical or
° MPI_LXOR	Logical exclusive or
° MPI_BAND	Binary and
° MPI_BOR	Binary or
° MPI_BXOR	Binary exclusive or
° MPI_MAXLOC	Maximum and location
° MPI_MINLOC	Minimum and location

How are collectives implemented in MPI?

- I specifically mention MPI as it enforces **certain semantic rules** (which also means that you can reimplement your own AllReduce if you have more relaxed semantics)
- Example: **MPI_AllReduce**

1. All processes must receive the same result vector;
2. Reduction must be performed in canonical order m0 + m1 + ⋯ + mp−1 (if the operation is not commutative);
3. The same reduction order and bracketing for all elements of the result vector is not strictly required, but should be strived for.

How are collectives implemented in MPI?

- **Lower bounds:**

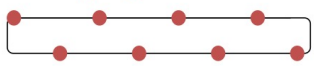
Communication	Latency	Bandwidth	Computation
Broadcast	$\lceil \log_2(p) \rceil \alpha$	$n\beta$	—
Reduce(-to-one)	$\lceil \log_2(p) \rceil \alpha$	$n\beta$	$\frac{p-1}{p} n\gamma$
Scatter	$\lceil \log_2(p) \rceil \alpha$	$\frac{p-1}{p} n\beta$	—
Gather	$\lceil \log_2(p) \rceil \alpha$	$\frac{p-1}{p} n\beta$	—
Allgather	$\lceil \log_2(p) \rceil \alpha$	$\frac{p-1}{p} n\beta$	—
Reduce-scatter	$\lceil \log_2(p) \rceil \alpha$	$\frac{p-1}{p} n\beta$	$\frac{p-1}{p} n\gamma$
Allreduce	$\lceil \log_2(p) \rceil \alpha$	$2\frac{p-1}{p} n\beta$	$\frac{p-1}{p} n\gamma$

Note: Pay particular attention to the conditions for the lower bounds given in the text.

Ernie Chan, Marcel Heimlich, Avi Purkayastha, and Robert Van De Geijn. "Collective communication: theory, practice, and experience." *Concurrency and Computation: Practice and Experience* 19, no. 13 (2007): 1749-1783.

AllGather

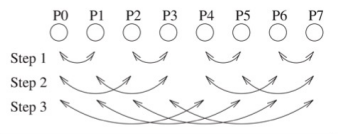
Ring Algorithm



$T_{ring} = \alpha (p-1) + \beta n (p-1)/p$

- **At time t**: send the data you received at time t-1 to your right, and receive new data from your left.
- **At time 0**, send your original data
- Optimal bandwidth, high latency
- Not as bad as it sounds if pipelined (NCCL exclusively uses uses pipelined ring algorithms for its collectives)

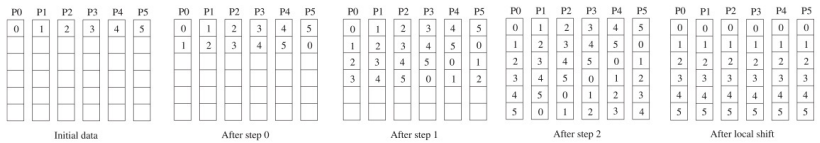
Recursive Doubling Algorithm



$T_{rec\text{-}dbl} = \alpha \lg(p) + \beta n (p-1)/p$

- **At time t**: process i exchanges (send/recv) all its current data (its original data plus anything received until then) with process $i \pm 2^t$
- Data exchanged at each step: n/p, 2n/p, 4n/p,…, $2^{\lg(p)-1}$ n/p
- Tricky for non-power-of-two

AllGather – The Bruck Algorithm



- **At time t**: process i receives all your current data from process $i+2^t$ and sends all of its current data to process $i-2^t$ (both modulo p)
- This regular exchange ends after $\lceil \lg(p) \rceil$ **steps**
- At the last communication step, instead of receiving/sending all current data, send/recv only the **top** $(p-2^{\lfloor \lg(p) \rfloor})$ **entries**
- Requires a final, local shift to get data in correct order.
- **For any p:** $T_{brock} = \alpha \lceil \lg(p) \rceil + \beta n (p-1)/p$
- By contrast, recursive doubling takes $2\lfloor \lg(p) \rfloor$ steps for non-power-of-two processor counts

AllGather Performance

- Similar ideas are used in other collectives (e.g. **recursive halving** instead of recursive doubling for **reduce-scatter**) with different local computations (e.g. for **allreduce**, perform a **local reduction** at each step instead of **concatenating** data as in allgather)

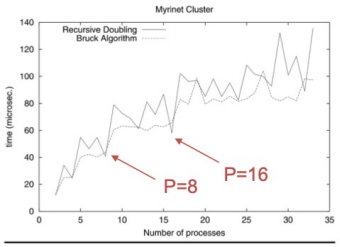


Fig. 3 Performance of recursive doubling versus Bruck allgather for power-of-two and non-power-of-two numbers of processes (message size 16 bytes per process).

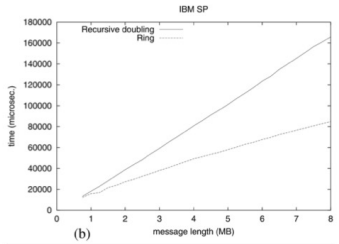


Fig. 5 Ring algorithm versus recursive doubling for long-message allgather (64 nodes). The size on the x-axis is the total amount of data gathered on each process.

Thakur, Rajeev, Rolf Rabenseifner, and William Gropp. "Optimization of collective communication operations in MPICH." *The International Journal of High Performance Computing Applications* 19.1 (2005): 49-66

Synchronization

- `MPI_Barrier( comm )`
- **Blocks until all processes in the group of the communicator `comm` call it.**
- **Almost never required in a parallel program**
  - **Occasionally useful in measuring performance and load balancing**

Nonblocking Collective Communication

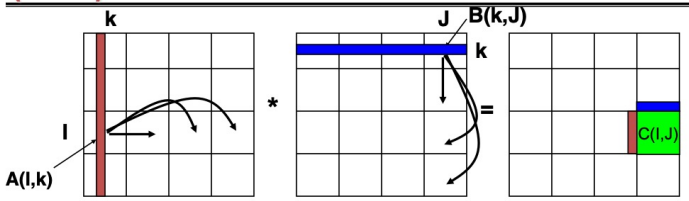
- Nonblocking variants of all collectives
  - **MPI_Ibcast(<bcast args>, MPI_Request *req);**
- Semantics:
  - Function returns no matter what
  - **No guaranteed progress (quality of implementation)**
  - Usual completion calls (wait, test) + mixing
  - Out-of order completion
- Restrictions:
  - No tags, in-order matching
  - Send and vector buffers may not be touched during operation
  - **No matching with blocking collectives**

Nonblocking Collective Communication

Semantic advantages:

- Enable asynchronous progression (and manual)
  - Software pipelining
- Decouple data transfer and synchronization
  - Noise resiliency!
- Allow overlapping communicators
  - See also neighborhood collectives
- Multiple outstanding operations at any time
  - Enables pipelining window

(recall) SUMMA



For k=0 to n-1 … or n/b-1 where b is the block size
… = # cols in A(I,k) and # rows in B(k,J)
for all I = 1 to p_r … in parallel
owner of A(I,k) broadcasts it to whole processor row
for all J = 1 to p_c … in parallel
owner of B(k,J) broadcasts it to whole processor column
Receive A(I,k) into Acol
Receive B(k,J) into Brow
C(myproc , myproc) = C(myproc , myproc) + Acol * Brow

(potentially overlapped) SUMMA in MPI – Part 1/3

```
void SUMMA(double *mA, double *mB, double *mc, int p_c)
{
   int row_color = rank / p_c; // p_c = sqrt(p) for simplicity
   MPI_Comm row_comm;
   MPI_Comm_split(MPI_COMM_WORLD, row_color, rank, &row_comm);

   int col_color = rank % p_c;
   MPI_Comm col_comm;
   MPI_Comm_split(MPI_COMM_WORLD, col_color, rank, &col_comm);

   double *mA1, *mA2, *mB1, *mB2;
   colsplit(mA, mA1, mA2); // split mA by the middle column
   rowsplit(mB, mB1, mB2); // split mA by the middle row

   if (col_color == 0)  memcpy(Atemp1, mA1, size)
   if (row_color == 0)  memcpy(Btemp1, mB1, size);

   MPI_Request reqs1[2];
   MPI_Request reqs2[2];
   MPI_Ibcast(Atemp1, size, MPI_DOUBLE, k, row_comm, &reqs1[0]);
   MPI_Ibcast(Btemp1, size, MPI_DOUBLE, k, col_comm, &reqs1[1]);
    …
```

(potentially overlapped) SUMMA in MPI – Part 2/3

```
…
for (int k = 0; k < p_c-1; ++k) {
     if (col_color == k)  memcpy(Atemp2, mA2, size);
     if (row_color == k)  memcpy(Btemp2, mB2, size);

     MPI_Ibcast(Atemp2,size,MPI_DOUBLE,k,row_comm,&reqs2[0]);
     MPI_Ibcast(Btemp2,size,MPI_DOUBLE,k,col_comm,&reqs2[1]);

     MPI_Waitall(reqs1, MPI_STATUS_IGNORE);
     SimpleDGEMM (Atemp1, Btemp1, mC, N/p, N/p, N/p);

     if (col_color == k)  memcpy(Atemp1, mA1, size);
     if (row_color == k)  memcpy(Btemp1, mB1, size);

     MPI_Ibcast(Atemp1,size,MPI_DOUBLE,k,row_comm,&reqs1[0]);
     MPI_Ibcast(Btemp1,size,MPI_DOUBLE,k,col_comm,&reqs1[1]);

     MPI_Waitall(reqs2, MPI_STATUS_IGNORE);
     SimpleDGEMM (Atemp2, Btemp2, mC, N/p, N/p, N/p);
}
…
```


(potentially overlapped) SUMMA in MPI – Part 3/3

```
…
 if (col_color == p-1)  memcpy(Atemp2, mA2, size);
 if (row_color == p-1)  memcpy(Btemp2, mB2, size);

 MPI_Ibcast(Atemp2,size,MPI_DOUBLE,k,row_comm,&reqs2[0]);
 MPI_Ibcast(Btemp2,size,MPI_DOUBLE,k,col_comm,&reqs2[1]);

 MPI_Waitall(reqs1, MPI_STATUS_IGNORE);
 SimpleDGEMM (Atemp1, Btemp1, mC, N/p, N/p, N/p);


 MPI_Waitall(reqs2, MPI_STATUS_IGNORE);
 SimpleDGEMM (Atemp2, Btemp2, mC, N/p, N/p, N/p);
}
…
```


Hybrid Programming with Threads

(slides by Gropp, Thakur, Balaji)

MPI and Threads

- MPI describes parallelism between *processes* (with separate address spaces)
- *Thread* parallelism provides a shared-memory model within a process
- OpenMP and Pthreads are common models
  - OpenMP provides convenient features for loop-level parallelism. Threads are created and managed by the compiler, based on user directives.
  - Pthreads provide more complex and dynamic approaches. Threads are created and managed explicitly by the user.

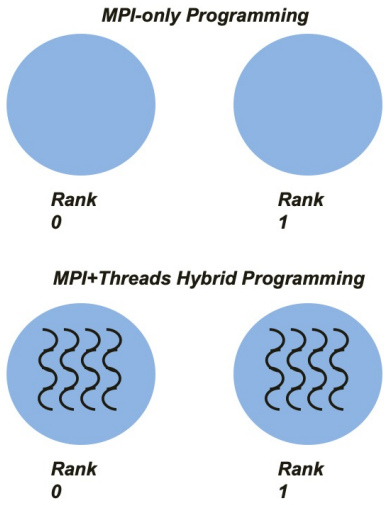
Programming for Multicore

° **Common options for programming multicore clusters**

- **All MPI**
  - **MPI between processes both within a node and across nodes**
  - **MPI internally uses shared memory to communicate within a node**
- **MPI + OpenMP**
  - **Use OpenMP within a node and MPI across nodes**
- **MPI + Pthreads**
  - **Use Pthreads within a node and MPI across nodes**

° **The latter two approaches are known as "hybrid programming"**

Hybrid Programming with MPI+Threads



° **In MPI-only programming, each MPI process has a single program counter**

° **In MPI+threads hybrid programming, there can be multiple threads executing simultaneously**

- **All threads share all MPI objects (communicators, requests)**
- **The MPI implementation might need to take precautions to make sure the state of the MPI stack is consistent**

MPI's Four Levels of Thread Safety

° MPI defines four levels of thread safety -- these are commitments the application makes to the MPI

- **MPI_THREAD_SINGLE:** only one thread exists in the application
- **MPI_THREAD_FUNNELED:** multithreaded, but only the main thread makes MPI calls (the one that called MPI_Init_thread)
- **MPI_THREAD_SERIALIZED:** multithreaded, but only one thread *at a time* makes MPI calls
- **MPI_THREAD_MULTIPLE**: multithreaded and any thread can make MPI calls at any time (with some restrictions to avoid races – see next slide)

° Thread levels are in increasing order

- If an application works in FUNNELED mode, it can work in SERIALIZED

° MPI defines an alternative to **MPI_Init**

- **MPI_Init_thread(requested, provided)**
  - *Application gives level it needs; MPI implementation gives level it supports*

MPI_THREAD_SINGLE

° **There are no threads in the system**

- **E.g., there are no OpenMP parallel regions**

```
int main(int argc, char ** argv)
{
    int buf[100];

    MPI_Init(&argc, &argv);

    for (i = 0; i < 100; i++)
        compute(buf[i]);

    /* Do MPI stuff */

    MPI_Finalize();

    return 0;
}
```

MPI_THREAD_FUNNELED

- All MPI calls are made by the master thread
  - Outside the OpenMP parallel regions
  - In OpenMP master regions

```
int main(int argc, char ** argv)
{
    int buf[100], provided;

    MPI_Init_thread(&argc, &argv, MPI_THREAD_FUNNELED, &provided);
    if (provided < MPI_THREAD_FUNNELED)
        MPI_Abort(MPI_COMM_WORLD, 1);

#pragma omp parallel for
    for (i = 0; i < 100; i++)
        compute(buf[i]);

    /* Do MPI stuff */

    MPI_Finalize();
    return 0;
}
```


MPI_THREAD_SERIALIZED

- Only one thread can make MPI calls at a time
  - Protected by OpenMP critical regions

```
int main(int argc, char ** argv)
{
    int buf[100], provided;

    MPI_Init_thread(&argc, &argv, MPI_THREAD_SERIALIZED, &provided);
    if (provided < MPI_THREAD_SERIALIZED)
        MPI_Abort(MPI_COMM_WORLD, 1);

#pragma omp parallel for
    for (i = 0; i < 100; i++) {
        compute(buf[i]);
#pragma omp critical
        /* Do MPI stuff */
    }

    MPI_Finalize();
    return 0;
}
```


MPI_THREAD_MULTIPLE

Any thread can make MPI calls any time (w/ restrictions)

```
int main(int argc, char ** argv)
{
    int buf[100], provided;

    MPI_Init_thread(&argc, &argv, MPI_THREAD_MULTIPLE, &provided);
    if (provided < MPI_THREAD_MULTIPLE)
        MPI_Abort(MPI_COMM_WORLD, 1);

#pragma omp parallel for
    for (i = 0; i < 100; i++) {
        compute(buf[i]);
        /* Do MPI stuff */
    }

    MPI_Finalize();

    return 0;
}
```


Threads and MPI

- An implementation is not required to support levels higher than MPI_THREAD_SINGLE; that is, an implementation is not required to be thread safe
- A fully thread-safe implementation will support MPI_THREAD_MULTIPLE
- A program that calls MPI_Init (instead of MPI_Init_thread) should assume that only MPI_THREAD_SINGLE is supported
- *A threaded MPI program that does not call MPI_Init_thread is an incorrect program (common user error we see)*

Specification of MPI_THREAD_MULTIPLE

- ***Ordering:*** When multiple threads make MPI calls concurrently, the outcome will be as if the calls executed sequentially in some (any) order
  - Ordering is maintained within each thread
  - User must ensure that collective operations on the same communicator, window, or file handle are correctly ordered among threads
    - E.g., cannot call a broadcast on one thread and a reduce on another thread on the same communicator
  - It is the user's responsibility to prevent races when threads in the same application post conflicting MPI calls
    - E.g., accessing an info object from one thread and freeing it from another thread
- ***Blocking:*** Blocking MPI calls will block only the calling thread and will not prevent other threads from running or executing MPI functions

Blocking Calls in MPI_THREAD_MULTIPLE:

Correct Example

	Process 0	*Process 1*
Thread 1	MPI_Recv(src=1)	MPI_Recv(src=0)
Thread 2	MPI_Send(dst=1)	MPI_Send(dst=0)

- An implementation must ensure that the above example never deadlocks for any ordering of thread execution (recall **ordering** rules in previous slide)
- That means the implementation cannot simply acquire a thread lock and block within an MPI function. It must release the lock to allow other threads to make progress (recall **blocking** rules in previous slide)

Ordering in MPI_THREAD_MULTIPLE:

Incorrect Example with Collectives

	Process 0	*Process 1*
Thread 1	MPI_Bcast(comm)	MPI_Bcast(comm)
Thread 2	MPI_Barrier(comm)	MPI_Barrier(comm)

- P0 and P1 can have different orderings of Bcast and Barrier
- Here the user must use some kind of synchronization to ensure that either thread 1 or thread 2 gets scheduled first on both processes
- Otherwise a broadcast may get matched with a barrier on the same communicator, which is not allowed in MPI

Ordering in MPI_THREAD_MULTIPLE:

Incorrect Example with Object Management

	Process 0	*Process 1*
Thread 1	MPI_Bcast(comm)	MPI_Bcast(comm)
Thread 2	MPI_Comm_free(comm)	MPI_Comm_free(comm)

- The user has to make sure that one thread is not using an object while another thread is freeing it
  - This is an ordering issue; the object might get freed before it is used

The Current Situation

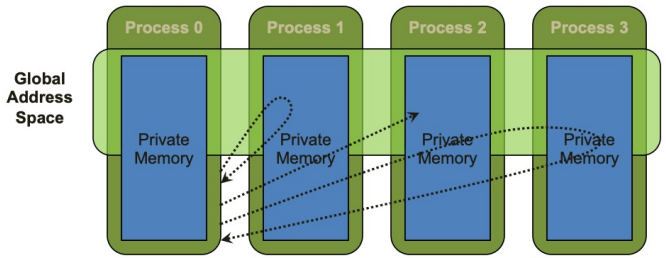
- All MPI implementations support MPI_THREAD_SINGLE
- They probably support MPI_THREAD_FUNNELED even if they don't admit it.
  - Does require thread-safe malloc
  - Probably OK in OpenMP programs
- Many (but not all) implementations support MPI_THREAD_MULTIPLE
  - Hard to implement efficiently though (lock granularity issue)
- "Easy" OpenMP programs (loops parallelized with OpenMP, communication in between loops) only need FUNNELED
  - So don't need "thread-safe" MPI for many hybrid programs
  - But watch out for Amdahl's Law!

One-sided Communication

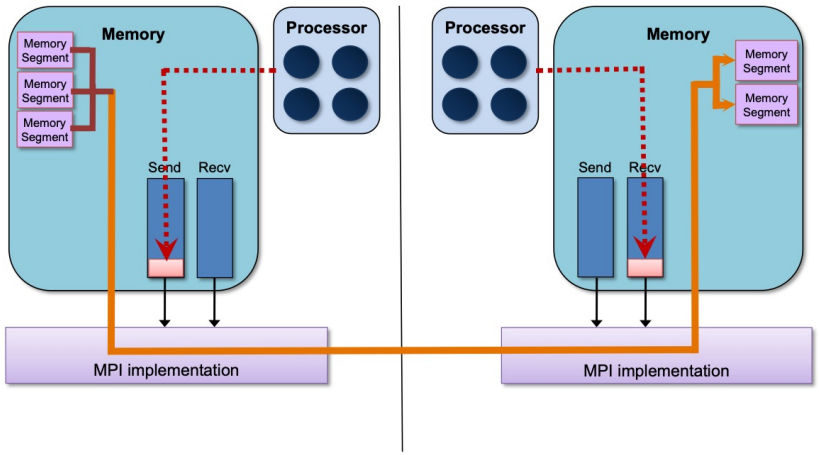
(slides by Gropp, Thakur, Balaji)

One-sided Communication

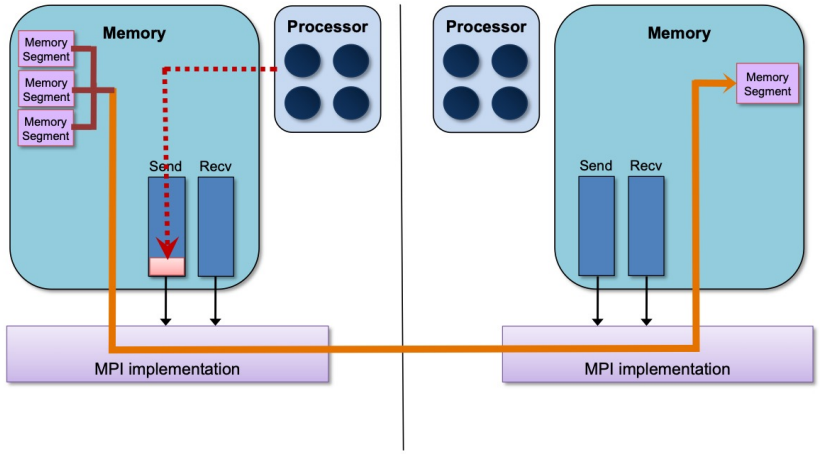
- **The basic idea of one-sided communication models is to decouple data movement with process synchronization**
  - **Should be able move data without requiring that the remote process synchronize**
  - **Each process exposes a part of its memory to other processes**
  - **Other processes can directly read from or write to this memory**



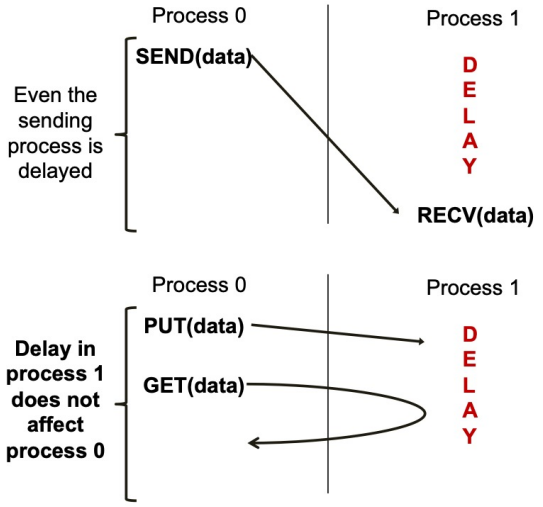
Two-sided Communication Example



One-sided Communication Example



Comparing One-sided and Two-sided Programming



What we need to know in MPI RMA

- **How to create remote accessible memory?**
- **Reading, Writing and Updating remote memory**
- **Data Synchronization**
- **Memory Model**

Creating Public Memory

- Any memory used by a process is, by default, only locally accessible
  - X = malloc(100);
- Once the memory is allocated, the user has to make an explicit MPI call to declare a memory region as remotely accessible
  - MPI terminology for remotely accessible memory is a “window”
  - A group of processes collectively create a “window”
- Once a memory region is declared as remotely accessible, all processes in the window can read/write data to this memory without explicitly synchronizing with the target process

Window creation models

- **Four models exist**
  - **MPI_WIN_CREATE**
    - **You already have an allocated buffer that you would like to make remotely accessible**
  - **MPI_WIN_ALLOCATE**
    - **You want to create a buffer and directly make it remotely accessible**
  - **MPI_WIN_CREATE_DYNAMIC**
    - **You don't have a buffer yet, but will have one in the future**
    - **You may want to dynamically add/remove buffers to/from the window**
  - **MPI_WIN_ALLOCATE_SHARED**
    - **You want multiple processes on the same node share a buffer**

MPI_WIN_ALLOCATE

```
int MPI_Win_allocate(MPI_Aint size, int disp_unit,
            MPI_Info info, MPI_Comm comm, void *baseptr,
            MPI_Win *win)
```

- Create a remotely accessible memory region in an RMA window
  - Only data exposed in a window can be accessed with RMA ops.
- Arguments:
  - size - size of local data in bytes (nonnegative integer)
  - disp_unit - local unit size for displacements, in bytes (positive integer)
  - info - info argument (handle)
  - comm - communicator (handle)
  - baseptr - pointer to exposed local data
  - win - window (handle)

Example with MPI_WIN_ALLOCATE

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);

    /* collectively create remote accessible memory in a window */
    MPI_Win_allocate(1000*sizeof(int), sizeof(int), MPI_INFO_NULL,
                     MPI_COMM_WORLD, &a, &win);

    /* Array 'a' is now accessible from all processes in
     * MPI_COMM_WORLD */

    MPI_Win_free(&win);

    MPI_Finalize(); return 0;
}
```


MPI_WIN_CREATE_DYNAMIC

```
int MPI_Win_create_dynamic(MPI_Info info, MPI_Comm comm,
                           MPI_Win *win)
```

- **Create an RMA window, to which data can later be attached**
  - **Only data exposed in a window can be accessed with RMA ops**
- **Initially "empty"**
  - **Application can dynamically attach/detach memory to this window by calling MPI_Win_attach/detach**
  - **Application can access data on this window only after a memory region has been attached**
- **Window origin is MPI_BOTTOM**
  - **Displacements are segment addresses relative to MPI_BOTTOM**
  - **Must tell others the displacement after calling attach**

Example with MPI_WIN_CREATE_DYNAMIC

```
int main(int argc, char ** argv)
{
    int *a;    MPI_Win win;

    MPI_Init(&argc, &argv);
    MPI_Win_create_dynamic(MPI_INFO_NULL, MPI_COMM_WORLD, &win);

    /* create private memory */
    a = (int *) malloc(1000 * sizeof(int));
    /* use private memory like you normally would */
    a[0] = 1;  a[1] = 2;

    /* locally declare memory as remotely accessible */
    MPI_Win_attach(win, a, 1000*sizeof(int));

    /* Array 'a' is now accessible from all processes */

    /* undeclare remotely accessible memory */
    MPI_Win_detach(win, a);  free(a);
    MPI_Win_free(&win);

    MPI_Finalize(); return 0;
}
```

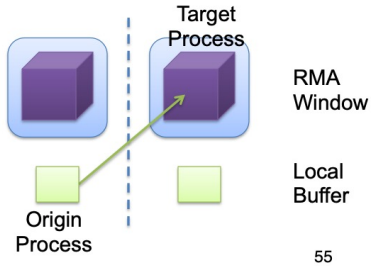
Data movement

- MPI provides ability to read, write and atomically modify data in remotely accessible memory regions
  - MPI_PUT
  - MPI_GET
  - MPI_ACCUMULATE
  - MPI_GET_ACCUMULATE
  - MPI_COMPARE_AND_SWAP
  - MPI_FETCH_AND_OP

Data movement: *Put*

```
MPI_Put(void * origin_addr, int origin_count,
      MPI_Datatype origin_datatype, int target_rank,
      MPI_Aint target_disp, int target_count,
      MPI_Datatype target_datatype, MPI_Win win)
```

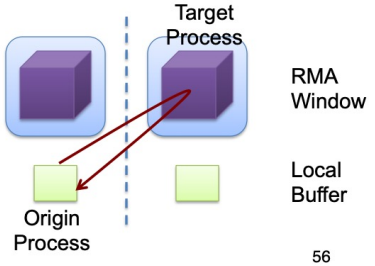
- Move data from origin, to target
- Separate data description triples for origin and target



Data movement: *Get*

```
MPI_Get(void * origin_addr, int origin_count,
      MPI_Datatype origin_datatype, int target_rank,
      MPI_Aint target_disp, int target_count,
      MPI_Datatype target_datatype, MPI_Win win)
```

- Move data to origin, from target



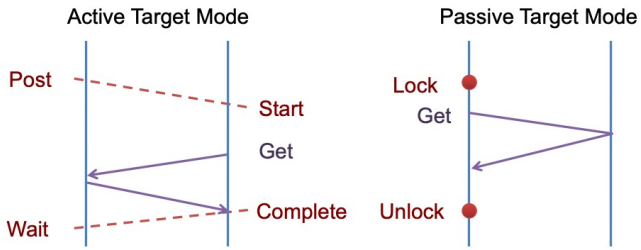
RMA Synchronization Models

- RMA data access model
  - When is a process allowed to read/write remotely accessible memory?
  - When is data written by process X is available for process Y to read?
  - RMA synchronization models define these semantics
- Three synchronization models provided by MPI:
  - Fence (active target)
  - Post-start-complete-wait (generalized active target)
  - Lock/Unlock (passive target)
- Data accesses occur within "epochs"
  - *Access epochs*: contain a set of operations issued by an origin process
  - *Exposure epochs*: enable remote processes to update a target's window
  - Epochs define ordering and completion semantics
  - Synchronization models provide mechanisms for establishing epochs
    - E.g., starting, ending, and synchronizing epochs

Ordering of Operations in MPI RMA

- No guaranteed ordering for Put/Get operations
- Result of concurrent Puts to the same location undefined
- Result of Get concurrent Put/Accumulate undefined
  - Can be garbage in both cases
- Result of concurrent accumulate operations to the same location are defined according to the order in which the occurred
  - Atomic put: Accumulate with op = MPI_REPLACE
  - Atomic get: Get_accumulate with op = MPI_NO_OP
- Accumulate operations from a given process are ordered by default
  - User can tell the MPI implementation that (s)he does not require ordering as optimization hint
  - You can ask for only the needed orderings: RAW (read-after-write), WAR, RAR, or WAW

Lock/Unlock: Passive Target Synchronization



- Passive mode: One-sided, *asynchronous* communication
  - Target does not participate in communication operation
- Shared memory-like model

Passive Target Synchronization

```
MPI_Win_lock(int locktype, int rank, int assert, MPI_Win win)

MPI_Win_unlock(int rank, MPI_Win win)
```

- Begin/end passive mode epoch
  - Target process does not make a corresponding MPI call
  - Can initiate multiple passive target epochs to different processes
  - Concurrent epochs to same process not allowed (affects threads)
- Lock type
  - SHARED: Other processes using shared can access concurrently
  - EXCLUSIVE: No other processes can access concurrently

Not Covered

- 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
- Task creation and destruction: change number of tasks during a run
  - Few implementations available