NON-BLOCKING COMMUNICATION

Non-blocking communication

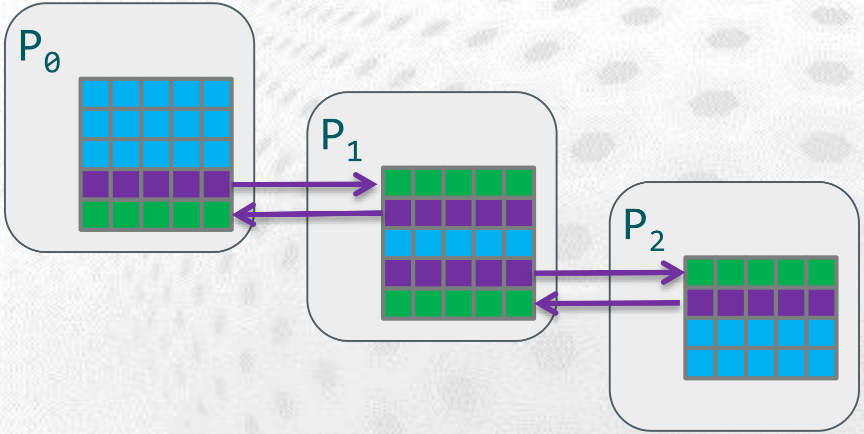
- Non-blocking sends and receives
  - `MPI_Isend` & `MPI_Irecv`
  - returns immediately and sends/receives in background
- Enables some computing concurrently with communication
- Avoids many common dead-lock situations
- Also non-blocking collective operations in MPI 3.0

Non-blocking communication

- Have to finalize send/receive operations
  - `MPI_Wait`, `MPI_Waitall`,…
    - Waits for the communication started with `MPI_Isend` or `MPI_Irecv` to finish (blocking)
  - `MPI_Test`,…
    - Tests if the communication has finished (non-blocking)
- You <u>can</u> mix non-blocking and blocking p2p routines
  - e.g., receive `MPI_Isend` with `MPI_Recv`

Typical usage pattern

```
MPI_Irecv(ghost_data)
MPI_Isend(border_data)
Compute(ghost_independent_data)
MPI_Waitall
Compute(border_data)
```



Non-blocking send

```
MPI_Isend(buf, count, datatype, dest, tag,
          comm, request)
```

Parameters

Similar to `MPI_Send` but has an additional request parameter

buf	send buffer that must not be written to until one has checked that the operation is over
request	a handle that is used when checking if the operation has finished (integer in Fortran, MPI_Request in C)

Order of sends

- Sends done in the specified order even for non-blocking routines
- Beware of badly ordered sends!

Non-blocking receive

```
MPI_Irecv(buf, count, datatype, source, tag,
          comm, request)
```

parameters similar to `MPI_Recv` but has no status parameter

buf	receive buffer guaranteed to contain the data only after one has checked that the operation is over
request	a handle that is used when checking if the operation has finished

Wait for non-blocking operation

```
MPI_Wait(request, status)
```

Parameters

request	handle of the non-blocking communication
status	status of the completed communication, see MPI_Recv

A call to MPI_WAIT returns when the operation identified by request is complete

Wait for non-blocking operations

`MPI_Waitall(count, requests, status)`

Parameters

count	number of requests
requests	array of requests
status	array of statuses for the operations that are waited for

A call to `MPI_Waitall` returns when *all* operations identified by the array of requests are complete

Additional completion operations

- other useful routines:
  - **`MPI_Waitany`**
  - **`MPI_Waitsome`**
  - **`MPI_Test`**
  - `MPI_Testall`
  - `MPI_Testany`
  - `MPI_Testsome`
  - `MPI_Probe`

Wait for non-blocking operations

```
MPI_Waitany(count, requests, index, status)
```

Parameters

count	number of requests
requests	array of requests
index	index of request that completed
status	status for the completed operations

A call to `MPI_Waitany` returns when one operation identified by the array of requests is complete

Wait for non-blocking operations

```
MPI_Waitsome(count, requests, done, index, status)
```

Parameters

count	number of requests
requests	array of requests
done	number of completed requests
index	array of indexes of completed requests
status	array of statuses of completed requests

A call to `MPI_Waitsome` returns when one or more operation identified by the array of requests is complete

Non-blocking test for non-blocking operations

```
MPI_Test(request, flag, status)
```

Parameters

request	request
flag	True if operation has completed
status	status for the completed operations

A call to `MPI_Test` is non-blocking. It allows one to schedule alternative activities while periodically checking for completion.

Example: Non-blocking broadcasting

```
MPI_Ibcast(buffer, count, datatype, root, comm, request)
```

buffer	data to be distributed
count	number of entries in buffer
datatype	data type of buffer
root	rank of broadcast root
comm	communicator
request	a handle that is used when checking if the operation has finished

Typical usage pattern

```
MPI_Ibcast(data,...,request)
! Do any kind of work not involving data
! ...
MPI_Wait(request)
```

Summary

- Non-blocking communication is usually the smarter way to do point-to-point communication in MPI
- Non-blocking communication realization
  - MPI_Isend
  - MPI_Irecv
  - MPI_Wait(all)
- MPI-3 contains also non-blocking collectives

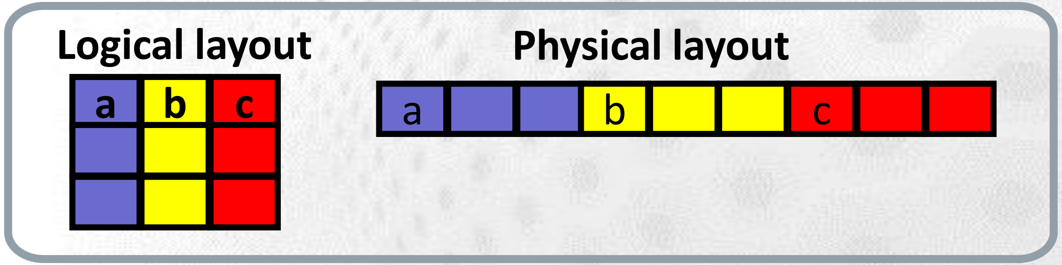
USER-DEFINED DATATYPES

MPI datatypes

- MPI datatypes are used for communication purposes
  - Datatype tells MPI where to take the data when sending or where to put data when receiving
- Elementary datatypes (MPI_INT, MPI_REAL, ...)
  - Different types in Fortran and C, correspond to languages basic types
  - Enable communication using contiguous memory sequence of identical elements (e.g. vector or matrix)

Sending a matrix row (Fortran)

- Row of a matrix is not contiguous in memory in Fortran
- Several options for sending a row:
  - Use several send commands for each element of a row
  - Copy data to temporary buffer and send that with one send command
  - Create a matching datatype and send all data with one send command



User-defined datatypes

- Use elementary datatypes as building blocks
- Enable communication of
  - Non-contiguous data with a single MPI call, e.g. rows or columns of a matrix
  - Heterogeneous data (structs in C, types in Fortran)
- Provide higher level of programming & efficiency
  - Code is more compact and maintainable
  - Communication of non-contiguous data is more efficient
- Needed for getting the most out of MPI I/O

User-defined datatypes

- User-defined datatypes can be used both in point-to-point communication and collective communication
- The datatype instructs where to take the data when sending or where to put data when receiving
  - Non-contiguous data in sending process can be received as contiguous or vice versa

Using user-defined datatypes

- A new datatype is created from existing ones with a datatype constructor
  - Several routines for different special cases
- A new datatype must be committed before using it

```
MPI_Type_commit(newtype)
```

newtype	the new datatype to commit

- A type should be freed after it is no longer needed

```
MPI_Type_free(newtype)
```

newtype	the datatype for decommision

Datatype constructors

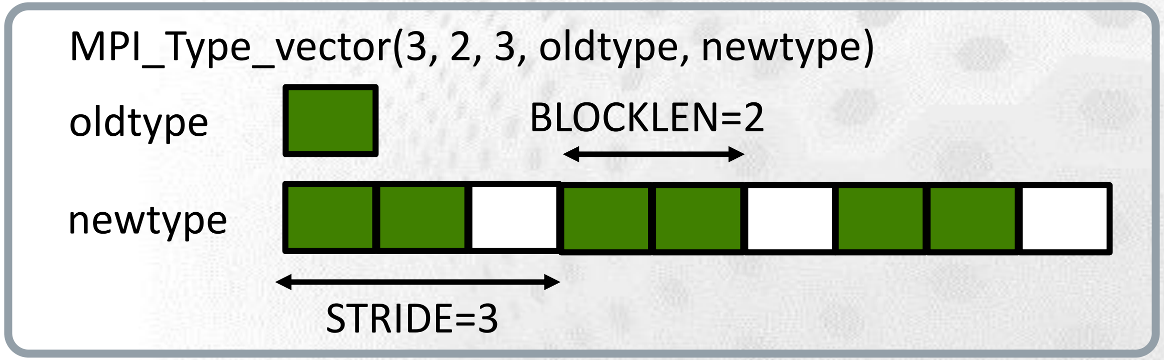
MPI_Type_contiguous	contiguous datatypes
MPI_Type_vector	regularly spaced datatype
MPI_Type_indexed	variably spaced datatype
MPI_Type_create_subarray	subarray within a multi-dimensional array
MPI_Type_create_hvector	like vector, but uses bytes for spacings
MPI_Type_create_hindexed	like index, but uses bytes for spacings
MPI_Type_create_struct	fully general datatype

MPI_TYPE_VECTOR

- Creates a new type from equally spaced identical block

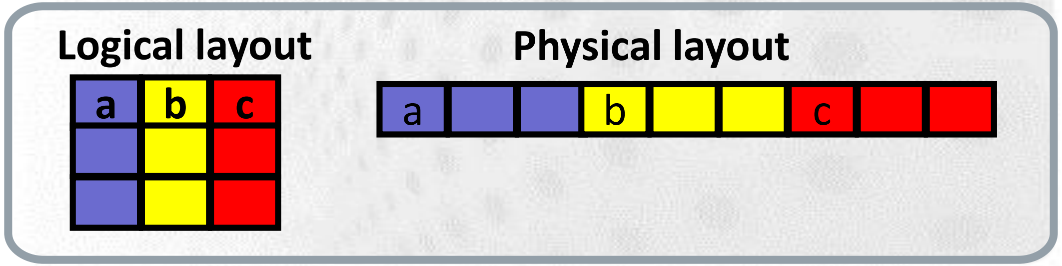
```
MPI_Type_vector(count, blocklen, stride, oldtype,
                newtype)
```

count	number of blocks
blocklen	number of elements in each block
stride	displacement between the blocks



Example: sending rows of matrix in Fortran

```
integer, parameter :: n=3, m=3
real, dimension(n,m) :: a
integer :: rowtype
! create a derived type
call mpi_type_vector(m, 1, n, mpi_real, rowtype, ierr)
call mpi_type_commit(rowtype, ierr)
! send a row
call mpi_send(a, 1, rowtype, dest, tag, comm, ierr)
! free the type after it is not needed
call mpi_type_free(rowtype, ierr)
```



MPI_TYPE_INDEXED

- Creates a new type from blocks comprising identical elements
  - The size and displacements of the blocks may vary

```
MPI_Type_indexed(count, blocklens, displs,
                        oldtype, newtype)
```

count	number of blocks
blocklens	lengths of the blocks (array)
displs	displacements (array) in extent of oldtypes

count = 3

blocklens = (/2,3,1/)

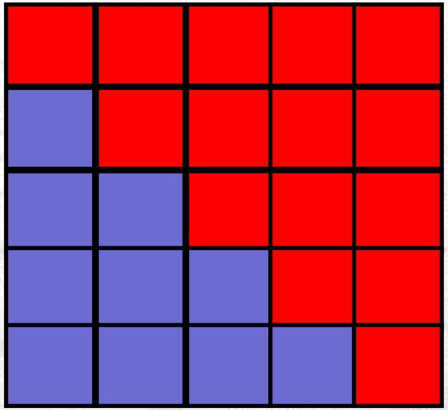
disps = (/0,3,8/)

oldtype

newtype

Example: an upper triangular matrix

```
/* Upper triangular matrix */
double a[100][100];
int  disp[100], blocklen[100], int i;
MPI_Datatype upper;
/* compute start and size of rows */
for (i=0;i<100;i++)
  {
    disp[i]=100*i+i;
    blocklen[i]=100-i;
  }
/* create a datatype for upper triangular matrix */
MPI_Type_indexed(100,blocklen,disp,MPI_DOUBLE,&upper);
MPI_Type_commit(&upper);
/* ... send it ... */
MPI_Send(a,1,upper,dest, tag, MPI_COMM_WORLD);
MPI_Type_free(&upper);
```



MPI_TYPE_CREATE_SUBARRAY

- Creates a type describing an *N*-dimensional subarray within an *N*-dimensional array

```
MPI_Type_create_subarray(ndims, sizes, subsizes,
                         offsets, order, oldtype, newtype)
```

ndims	number of array dimensions
sizes	number of array elements in each dimension (array)
subsizes	number of subarray elements in each dimension (array)
offsets	starting point of subarray in each dimension (array)
order	storage order of the array. Either MPI_ORDER_C or MPI_ORDER_FORTRAN

Example: subarray

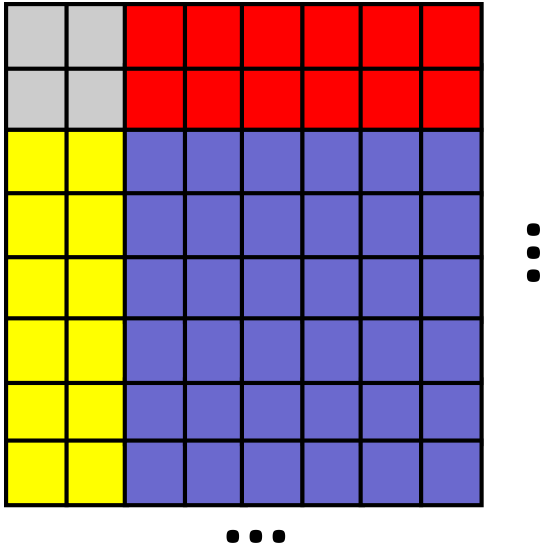
```
int array_size[2]     = {5,5};
int subarray_size[2]  = {2,2};
int subarray_start[2] = {1,1};
MPI_Datatype subtype;
double **array

for (i=0; i<array_size[0]; i++)
  for (j=0; j<array_size[1]; j++)
    array[i][j] = rank;
MPI_Type_create_subarray(2, array_size, subarray_size, subarray_start,
                         MPI_ORDER_C, MPI_DOUBLE, &subtype);
MPI_Type_commit(&subtype);
if (rank==0)
  MPI_Recv(array[0], 1, subtype, 1, 123, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
if (rank==1)
  MPI_Send(array[0], 1, subtype, 0, 123, MPI_COMM_WORLD);
```

```
Rank 0: original array
  0.0   0.0   0.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0
Rank 0: array after receive
  0.0   0.0   0.0   0.0   0.0
  0.0   1.0   1.0   0.0   0.0
  0.0   1.0   1.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0
  0.0   0.0   0.0   0.0   0.0
```

Example: halo exchange with user defined types

Two-dimensional grid with two-element ghost layers

512 x 512 (+ halo)

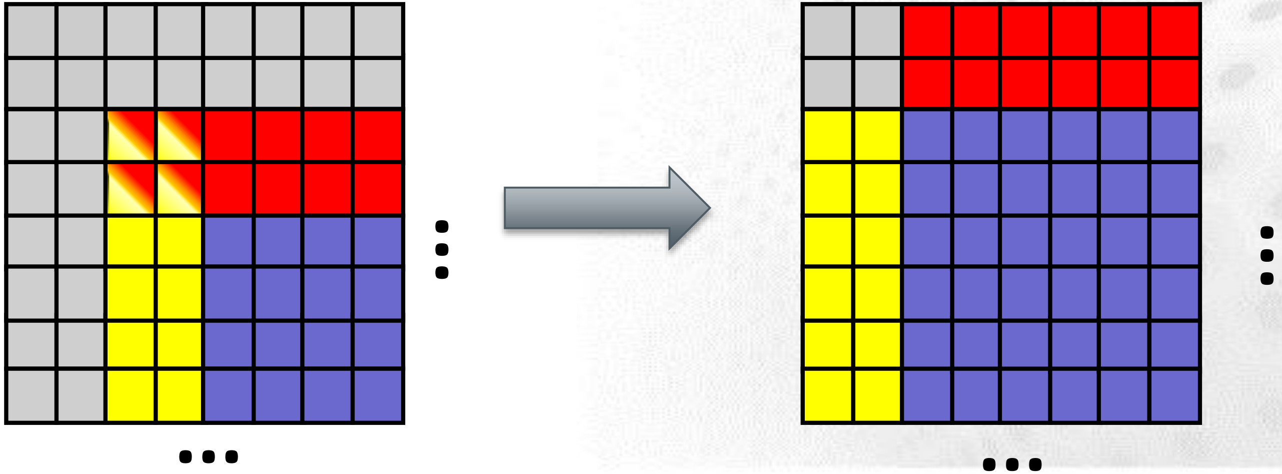


```
int array_size[2] = {512 + 2+2, 512 + 2+2};
int x_size[2] = {512,2};
int offset[2] = {0,0};
MPI_Type_create_subarray(2, array_size, x_size,
      offset, MPI_ORDER_C, MPI_DOUBLE,
      &x_boundary);
```

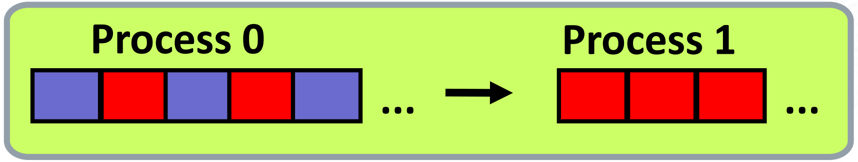
```
int y_size[2] = {2,512};
MPI_Type_create_subarray(2, array_size, y_size,
      offset, MPI_ORDER_C, MPI_DOUBLE,
      &y_boundary);
```

Example: halo exchange with user defined types

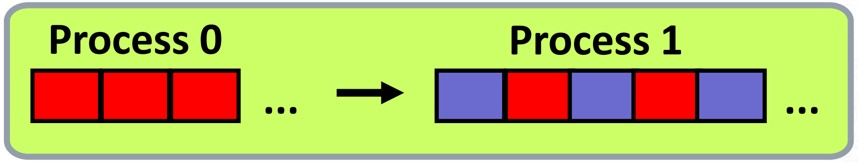
```
MPI_Sendrecv(array(2,2), 1, x_boundary, left, tag_left,
             array(2,0), 1, x_boundary, right, tag_right,
             MPI_COMM_WORLD, MPI_STATUS_IGNORE);

MPI_Sendrecv(array(2,2), 1, y_boundary, down, tag_down,
             array(0,2), 1, y_boundary, up, tag_up,
             MPI_COMM_WORLD, MPI_STATUS_IGNORE);
...
```



From non-contiguous to contiguous data




```
if (myid == 0)
   MPI_Type_vector(n, 1, 2,
                        MPI_FLOAT, &newtype)
   ...
   MPI_Send(A, 1, newtype, 1, ...)
else
   MPI_Recv(B, n, MPI_FLOAT, 0, ...)
```




```
if (myid == 0)
   MPI_Send(A, n, MPI_FLOAT, 1, ...)
else
   MPI_Type_vector(n, 1, 2, MPI_FLOAT,
                        &newtype)
   ...
   MPI_Recv(B, 1, newtype, 0, ...)
```

Performance

- Performance depends on the datatype - more general datatypes are often slower
- Overhead is potentially reduced by:
  - Sending one long message instead of many small messages
  - Avoiding the need to pack data in temporary buffers
- Performance should be tested on target platforms

Performance

- Example: Sending a row (in C) of 512x512 matrix on Cray XC30
  - Several sends: 10 ms
  - Manual packing: 1.1 ms
  - User defined type: 0.6 ms

Summary

- Derived types enable communication of non-contiguous or heterogenous data with single MPI calls
  - Improves maintainability of program
  - Allows optimizations by the system
  - Performance is implementation dependent
- Life cycle of derived type: create, commit, free
- MPI provides constructors for several specific types

COMMUNICATION TOPOLOGIES

Process topologies

- MPI process topologies allow for simple referencing scheme of processes
  - Process topology defines a new communicator
  - We focus on Cartesian topologies,
    although graph topologies are also supported
- MPI topologies are virtual
  - No relation to the physical structure of the computer
  - Data mapping "more natural" only to the programmer
- Usually no performance benefits
  - But code becomes more compact and readable

Creating a communicator ordered in Cartesian grid

```
MPI_Cart_create(oldcomm, ndims, dims, periods, reorder,
                newcomm)
```

`oldcomm`	communicator
`ndims`	dimension of the Cartesian topology
`dims`	integer array (size ndims) that defines the number of processes in each dimension
`periods`	array that defines the periodicity of each dimension
`reorder`	is MPI allowed to renumber the ranks
`newcomm`	new Cartesian communicator

Translating rank to coordinates

```
MPI_Cart_coords(comm, rank, maxdim, coords)
```

`comm`	Cartesian communicator
`rank`	rank to convert
`maxdim`	dimension of coords
`coords`	coordinates in Cartesian topology that corresponds to rank

- Checking the Cartesian communication topology coordinates for a specific rank

Translating coordinates to rank

```
MPI_Cart_rank(comm, coords, rank)

comm    Cartesian communicator
coords  array of coordinates
rank    a rank corresponding to coords
```

- Checking the rank of the process at specific Cartesian communication topology coordinates

Creating a Cartesian communication topology

```fortran
dims(1)=4
dims(2)=4
period=(/ .true., .true. /)

call mpi_cart_create(mpi_comm_world, 2, &
    dims, period, .true., comm2d, rc)
call mpi_comm_rank(comm2d, my_id, rc)
call mpi_cart_coords(comm2d, my_id, 2, &
    coords, rc)
```

0 (0,0)	1 (0,1)	2 (0,2)	3 (0,3)
4 (1,0)	5 (1,1)	6 (1,2)	7 (1,3)
8 (2,0)	9 (2,1)	10 (2,2)	11 (2,3)
12 (3,0)	13 (3,1)	14 (3,2)	15 (3,3)

How to communicate in a topology

```
MPI_Cart_shift(comm, direction, displ, source, dest)
```

`comm`	Cartesian communicator
`direction`	shift direction (0 or 1 in 2D)
`displ`	shift displacement (1 for next cell etc, < 0 for source from "down"/"right“ directions)
`source`	rank of source process
`dest`	rank of destination process

- We shift the grid to define sources/destinations

Note that both source and dest are output parameters. The coordinates of the calling task is implicit input.

With a non-periodic grid, source or dest can land outside of the grid; then MPI_PROC_NULL is returned.

Halo exchange

```
dims(1)=4
dims(2)=4
period =(/ .true. , .true. /)

call mpi_cart_create(mpi_comm_world, 2,&
    dims, period, .true., comm2d, rc)
call mpi_cart_shift(comm2d,0,1,nbr_up,nbr_down,rc)
call mpi_cart_shift(comm2d,1,1,nbr_left,nbr_right,rc)
...
call mpi_sendrecv(hor_send, msglen, mpi_double_precision, nbr_left,&
     tag_left, hor_recv, msglen, mpi_double_precision, nbr_right,&
     tag_left, comm2d, mpi_status_ignore, rc)
...
call mpi_sendrecv(vert_send, msglen, mpi_double_precision, nbr_up,&
     tag_up, vert_recv, msglen, mpi_double_precision, nbr_down,&
     tag_up, comm2d, mpi_status_ignore, rc)
...
```

0 (0,0)	1 (0,1)	2 (0,2)	3 (0,3)
4 (1,0)	5 (1,1)	6 (1,2)	7 (1,3)
8 (2,0)	9 (2,1)	10 (2,2)	11 (2,3)
12 (3,0)	13 (3,1)	14 (3,2)	15 (3,3)

ONE-SIDED COMMUNICATION

Communication in MPI

- Two components of message-passing: sending and receiving
- One-sided communication
  - Only single process calls data movement functions (*put* or *get*) – remote memory access (RMA)
  - Communication patterns specified by only a single process
  - Always non-blocking

Why one-sided communication?

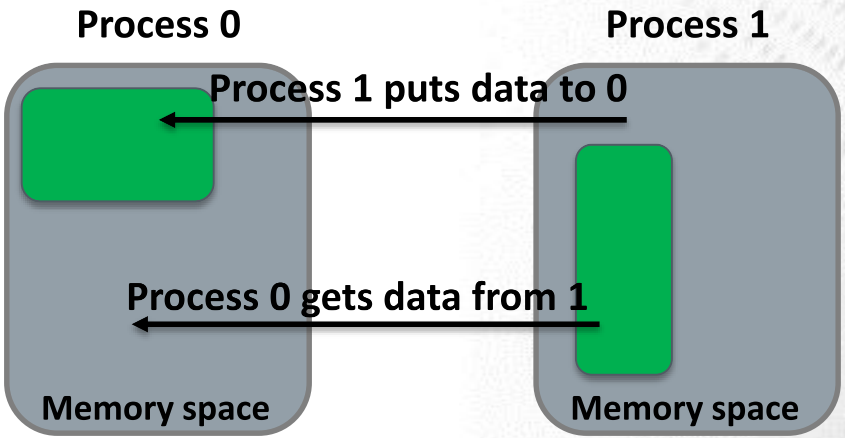
- Certain algorithms featuring unstrucutred communication easier to implement
- Potentially reduced overhead and improved scalability
- Hardware support for remote memory access has been restored in most current-generation architectures

Origin and target

- Origin process: a process which calls data movement function
- Target process: a process whose memory is accessed

Remote memory access window

- *Window* is a region in process's memory which is made available for remote operations
- Windows are created by collective calls
- Windows may be different in different processes



Data movement operations in MPI

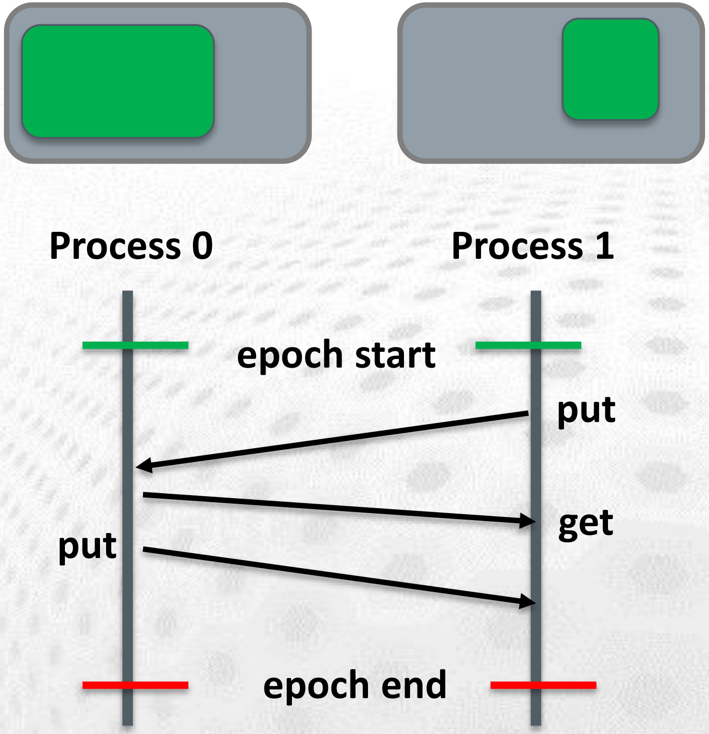
- PUT data to the memory in target process
  - From local buffer in origin to the window in target
- GET data from the memory of target process
  - From the window in target to the local buffer in origin
- ACCUMULATE data in target process
  - Use local buffer in origin and update the data (e.g. add the data from origin) in the window in target
  - One-sided reduction

Synchronization

- Communication takes place within *epochs*
  - Synchronization calls start and end an epoch
  - There can be multiple data movement calls within an epoch
  - An epoch is specific to a particular window
- Active synchronization:
  - Both origin and target perform synchronization calls
- Passive synchronization:
  - No MPI calls at target process

One-sided communication in a nutshell

- Define a memory window
- Start an epoch
  - Target: exposure epoch
  - Origin: access epoch
- GET, PUT, and/or ACCUMULATE data
- Complete the communications by ending the epoch



Creating a window

```
MPI_Win_create(base, size, disp_unit, info, comm, win)

base      (pointer to) local memory to expose for RMA
size      size of a window in bytes
disp_unit local unit size for displacements in bytes
info      hints for implementation
comm      communicator
win       handle to window
```

- The window object is deallocated with

```
MPI_Win_free(win)
```

Starting and ending an epoch

```
MPI_Win_fence(assert, win)

assert     optimize for specific usage. Valid values are
           ”0”, MPI_MODE_NOSTORE, MPI_MODE_NOPUT,
           MPI_MODE_NOPRECEDE, MPI_MODE_NOSUCCEED
win        window handle
```

- Used both for starting and ending an epoch
  - Should both precede and follow data movement calls
- Collective, barrier-like operation

Data movement: Put

```
MPI_Put(origin, origin_count, origin_datatype,
        target_rank, target_disp, target_count,
        target_datatype, win)
```

origin	(pointer to) local data to be send to target
origin_count	number of elements to put
origin_datatype	MPI datatype for local data
target_rank	rank of the target task
target_disp	starting point in target window
target_count	number of elements in target
target_datatype	MPI datatype for remote data
win	RMA window

Data movement: Get

```
MPI_Get(origin, origin_count, origin_datatype,
        target_rank, target_disp, target_count,
        target_datatype, win)
```

origin	(pointer to) local buffer in which to receive the data
origin_count	number of elements to get
origin_datatype	MPI datatype for local data
target_rank	rank of the target task
target_disp	starting point in target window
target_count	number of elements from target
target_datatype	MPI datatype for remote data
win	RMA window

Data movement: Accumulate

```
MPI_Accumulate(origin, origin_count, origin_datatype,
               target_rank, target_disp, target_count,
               target_datatype, op, win)
```

origin	(pointer to) local data to be accumulated
origin_count	number of elements to put
origin_datatype	MPI datatype for local data
target_rank	rank of the target task
target_disp	starting point in target window
target_count	number of elements for target
target_datatype	MPI datatype for remote data
op	accumulation operation (as in MPI_Reduce)
win	RMA window

Simple example: Put

```
...
  int data;
  MPI_Win window;

  data = rank;
  // Create window
  MPI_Win_create(&data, sizeof(int), sizeof(int), MPI_INFO_NULL,
                 MPI_COMM_WORLD, &window);
  ...
  MPI_Win_fence(0, window);
  if (rank == 0)
      MPI_Put(&data, 1, MPI_INT, 1, 0, 1, MPI_INT, window);
  MPI_Win_fence(0, window);
  ...
  MPI_Win_free(&window);
```

Limitations for data access

- Compatibility of local and remote operations when multiple processes access a window during an epoch

Local/ remote	Load	Store	Get	Put	Acc
Load					
Store					
Get					
Put					
Acc					

No limitations

Operations on non-overlapping parts of window allowed

Not allowed

Advanced synchronization

- Assert arguments for `MPI_Win_fence`:
  `MPI_MODE_NOSTORE`
  The local window was not updated by local stores (or local get or receive calls) since last synchronization
  `MPI_MODE_NOPUT`
  The local window will not be updated by put or accumulate calls after the fence call, until the ensuing (fence) synchronization
  `MPI_MODE_NOPRECEDE`
  The fence does not complete any sequence of locally issued RMA calls
  `MPI_MODE_NOSUCCEED`
  The fence does not start any sequence of locally issued RMA calls

Advanced synchronization

- More control on epochs can be obtained by starting and ending the exposure and access epochs separately
- Target: Exposure epoch
  - Start: `MPI_Win_post`
  - End: `MPI_Win_wait`
- Origin: Access epoch
  - Start: `MPI_Win_start`
  - End: `MPI_Win_compete`

Enhancements in MPI-3

- New window creation function: `MPI_Win_allocate`
  - Allocate memory and create a window at the same time
- Dynamic windows: `MPI_Win_create_dynamic`, `MPI_Win_attach`, `MPI_Win_detach`
  - Non-collective exposure of memory

Enhancements in MPI-3

- New data movement operations: `MPI_Get_accumulate`, `MPI_Fetch_and_op`, `MPI_Compare_and_swap`
- New memory model `MPI_Win_allocate_shared`
  - Allocate memory which is shared between MPI tasks
- Enhancements for passive target synchronization

Performance considerations

- Performance of the one-sided approach is highly implementation-dependent
- Maximize the amount of operations within an epoch
- Provide the assert parameters for MPI_Win_fence

Summary

- One-sided communication allows communication patterns to be specified from a single process
- Can reduce synchronization overheads and provide better performance especially on recent hardware
- Basic concepts:
  - Creation of the memory window
  - Communication epoch
  - Data movement operations (MPI_Put, MPI_Get etc)