# MPI Tutorial

## Desert Code Camp

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http://github.com/adigiro/mpitutorial

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# What is MPI?

## What is message passing?

- Literally, the sending and receiving of messages between tasks
- Commonly used in distributed systems
- Capabilities include sending data, performing operations on data, and synchronization between tasks

## Memory Model

Each process has its own address space, and no way to get at another's, so it is necessary to send/receive data



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# Alternatives

- OpenMP
- PGAS languages
  (Partitioned Global Address Space)
  - UPC
  - Co-Array Fortran
- Global Arrays Library
- Hybrids with Message Passing are possible

# MPI-1

## MPI-1 - Message Passing Interface (v. 1.2)

- library standard defined by committee of vendors, implementers, and parallel programmers
- used to create parallel SPMD codes based on explicit message passing

Available on almost all parallel machines with C/C++ and Fortran bindings (and occasionally with other bindings)

## About 125 routines, total

- 6 basic routines
- the rest include routines of increasing generality and specificity



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# MPI-2

## Includes features left out of MPI-1

- one-sided communications
- dynamic process control
- more complicated collectives

## Implementations

- not quickly undertaken after the standard document was released (in 1997)
- now OpenMPI, MPICH2 (and its descendants), and the vendor implemenations are pretty complete or fully complete



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# Why Learn MPI?

- MPI is a standard
  - Public domain version easily to install
  - Vendor-optimized version available on most communication hardware
- MPI applications can be fairly portable
- MPI is expressive: MPI can be used for many different models of computation, therefore can be used with many different applications.
- MPI is “assembly language of parallel processing”: low level but efficient.



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# Initialization and Termination

- Must include header files
- All processes must initialize and finalize MPI (each is a collective call).

C

```
#include <mpi.h>
int main(int argc, char *argv[] ) {
  int ierr;
  ierr = MPI_Init(&argc, &argv);
  ...
  ierr = MPI_Finalize();
}
```

Fortran

```
program init_finalize
  include 'mpif.h'
  call mpi_init(ierr)
  ...
  call mpi_finalize(ierr)
end program
```



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# Setting up Communicators

## Communicators

- collections of processes that can communicate with each other
- Multiple communicators can co-exist
- Each communicator answers two questions:
  - How many processes exist in this communicator?
  - Which process am I?
- MPI_COMM_WORLD encompasses all processes and is defined by default



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# Setting up Communicators

C

```c
#include <mpi.h>
int main(int argc, char *argv[] ) {
  int ierr, myrank, procs;

  ierr = MPI_Init(&argc, &argv);
  ierr = MPI_Comm_size(MPI_COMM_WORLD, &procs);
  ierr = MPI_Comm_rank(MPI_COMM_WORLD, &myrank);

  ierr = MPI_Finalize();
}
```

Fortran

```fortran
program init_finalize
  include 'mpif.h'

  call mpi_init(ierr)
  call mpi_comm_size(MPI_COMM_WORLD, procs  ,ierr)
  call mpi_comm_rank(MPI_COMM_WORLD, myrank ,ierr)

  call mpi_finalize(ierr)
end program
```



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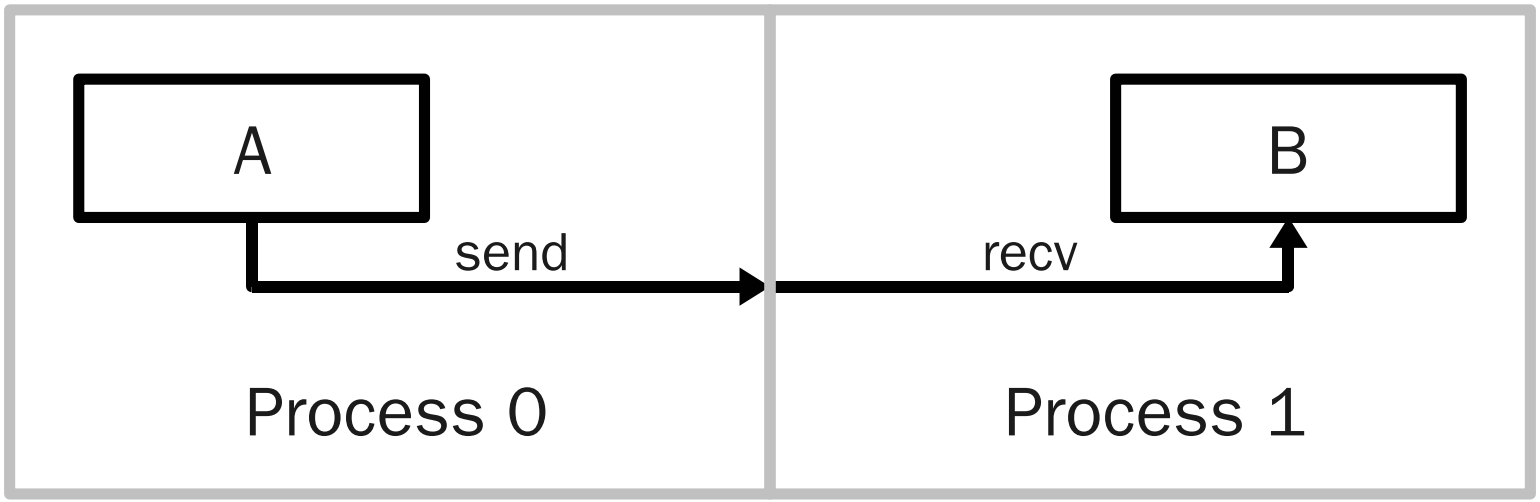
# Point to Point Communication

- Sending data from one point (process/task) to another point (process/task)
- One task sends while another receives




- **MPI_Send()**: A blocking call which returns only when data has been sent from its buffer
- **MPI_Recv()**: A blocking receive which returns only when data has been received onto its buffer



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# Point to Point Communication

## Parameters:

- void* data: actual data being passed
- int count: number of type values in data
- MPI_Datatype type: data type of data
- int dest/src: rank of the process this call is sending to or receiving from. src can also be wildcard MPI_ANY_SOURCE
- int tag: simple identifier that must match between sender/receiver, or the wildcard MPI_ANY_TAG
- MPI_Comm comm: communicator that must match between sender/receiver – no wildcards
- MPI_Status* status: returns information on the message received (receiving only), e.g. which source if using MPI_ANY_SOURCE
- INTEGER ierr: place to store error code (Fortran only. In C/C++ this is the return value of the function call)

C

```
MPI_Send(data, count, type, dest, tag, comm)
MPI_Recv(data, count, type, src,  tag, comm, &status)
```

Fortran

```
mpi_send(data, count, type, dest, tag, comm, ierr)
mpi_recv(data, count, type, src, tag, comm, status, ierr)
```

# Point to Point Communication

- Recall that all tasks execute the same code, conditionals are often needed

C

```
MPI_Comm_rank(comm, &myrank);

if (myrank==0) {
  MPI_Send( /*buffer*/, /*target=*/ 1, /*tag=*/ 0, comm);
} else if (myrank==1) {
  MPI_Recv( /*buffer*/, /*source=*/ 0, /*tag=*/ 0, comm);
}
```



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# Examples

C

```
#include "mpi.h"
main(int argc, char **argv){
  int myrank, procs, ierr; double a[2];
  MPI_Status status;
  MPI_Comm icomm = MPI_COMM_WORLD;
  ierr = MPI_Init(&argc, &argv);
  ierr = MPI_Comm_rank(icomm, &myrank);
  ierr = MPI_Comm_size(icomm, &procs);
  if(myrank == 0){
    a[0] = myrank; a[1] = myrank+1;
    ierr = MPI_Send(a,2,MPI_DOUBLE, 1,9, icomm);
  }
  else if (myrank == 1){
    ierr = MPI_Recv(a,2,MPI_DOUBLE, 0,9,icomm,&status);
    printf("PE %d, A array= %f %f\n",myrank,a[0],a[1]);
  }
  MPI_Finalize();
}
```

# Examples

Fortran

```
program sr
  include "mpif.h"
  real*8,  dimension(2)                    :: A
  integer, dimension(MPI_STATUS_SIZE) :: istat
  icomm = MPI_COMM_WORLD
  call mpi_init(ierr)
  call mpi_comm_rank(icomm,mype,ierr)
  call mpi_comm_size(icomm,np  ,ierr);

  if(mype.eq.0) then
    a(1) = real(ipe); a(2) = real(ipe+1)
    call mpi_send(A,2,MPI_REAL8, 1,9,icomm, ierr)
  else if (mype.eq.1) then
    call mpi_recv(A,2,MPI_REAL8, 0,9,icomm, istat,ierr)
    print*,"PE ",mype,"received A array =",A
  endif

  call mpi_finalize(ierr)
end program
```



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# Broadcast

- What if one processor wants to send to everyone else?

C

```
if (mytid == 0 ) {
  for (tid=1; tid<ntids; tid++) {
    MPI_Send( (void*)a, /* target= */ tid, ... );
  }
} else {
  MPI_Recv( (void*)a, 0, ... );
}
```

- Implements a very naive, serial broadcast
- Too primitive
  - leaves no room for the OS / switch to optimize
  - leaves no room for fancy algorithms
- Too slow: calls may wait for completion.



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# MPI Collective Communications

- Collective Communication
  - Communication pattern that involves all processes within a communicator
- There are three basic types of collective communications:
  - Synchronization
  - Data movement
  - Computation w/ movement
- MPI Collectives are all blocking
- MPI Collectives do not use message tags

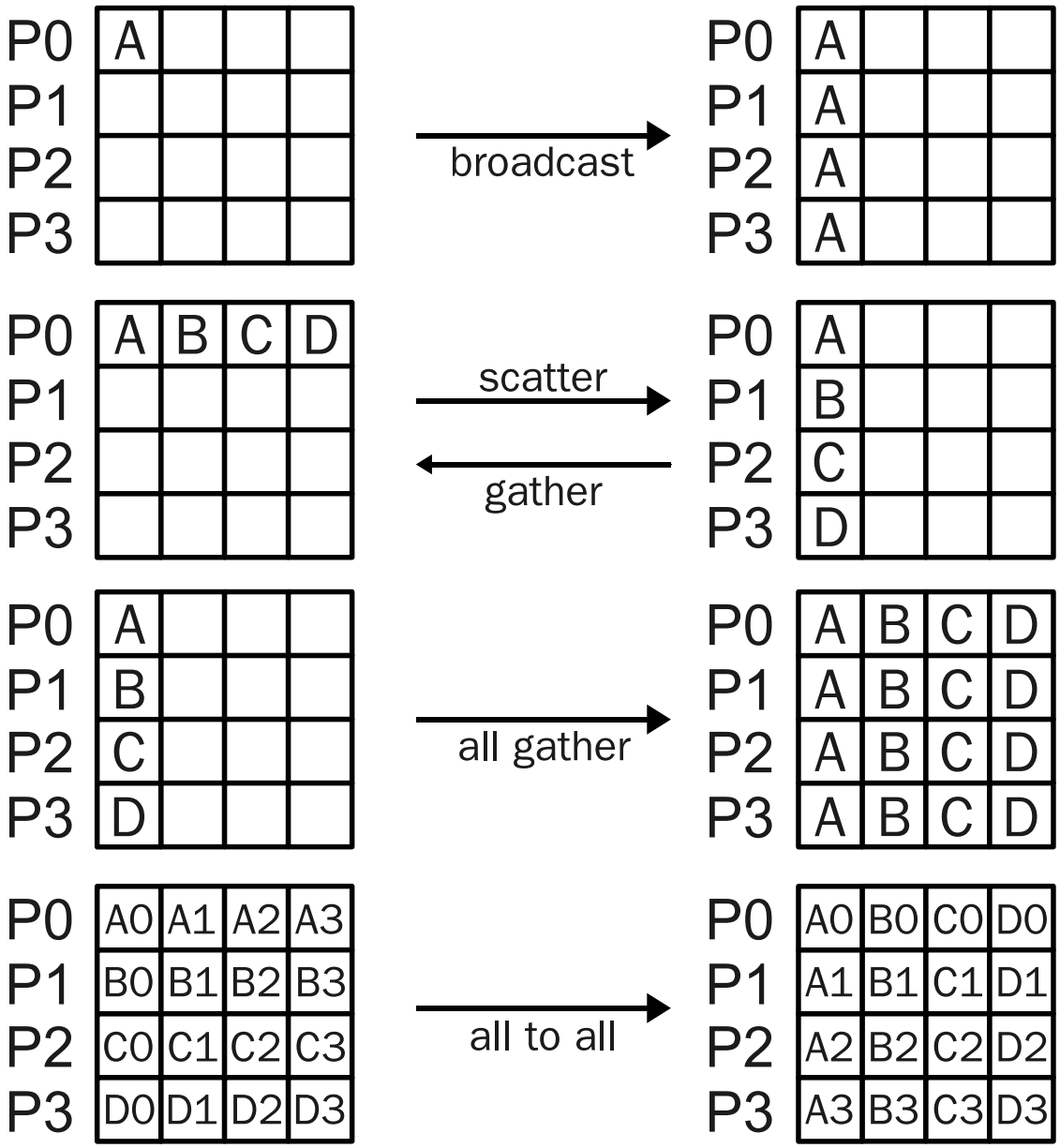
# Synchronization

## Barrier

- `MPI_Barrier(comm)`
- `mpi_barrier(comm, ierr)`

Function blocks until all tasks in comm call it.

# Collective Data Movements



# Broadcast

- `MPI_Bcast(data, count, type, root, comm)`
- `mpi_bcast(data, count, type, root, comm, ierr)`

Sends data from the root process to all communicator members.



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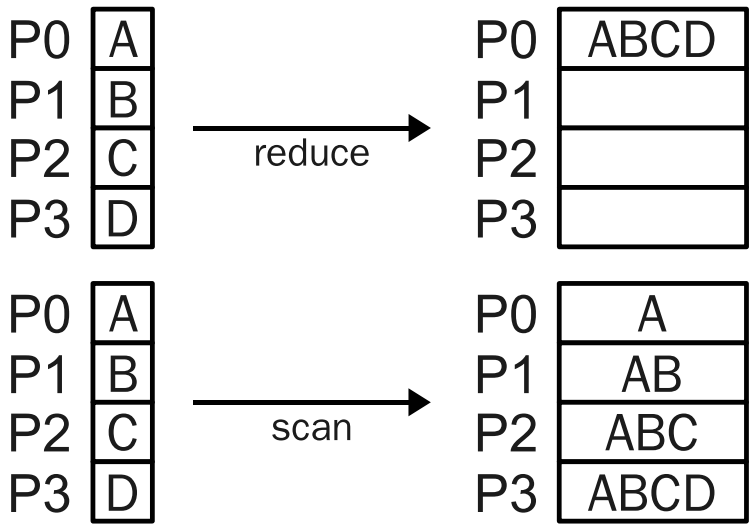
# Collective Computations



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# Collective Computations

- `MPI_Reduce(data, result, count, type, op, root, comm)`
- `mpi_reduce(data, result, count, type, op, root, comm, ierr)`

## Operations

- MPI_SUM
- MPI_PROD
- MPI_MAX
- MPI_MIN
- MPI_MAXLOC
- MPI_MINLOC

# Example

C

```
#include <mpi.h>
#define WCOMM MPI_COMM_WORLD
main(int argc, char **argv){
  int npes, mype, ierr;
  double sum, val; int calc, knt=1;
  ierr = MPI_Init(&argc, &argv);
  ierr = MPI_Comm_size(WCOMM, &npes);
  ierr = MPI_Comm_rank(WCOMM, &mype);

  val = (double) mype;

  ierr = MPI_Allreduce(&val, &sum, knt,
                       MPI_DOUBLE, MPI_SUM,WCOMM);

  calc = (npes-1 +npes%2)*(npes/2);
  printf(" PE: %d sum=%5.0f calc=%d\n",mype,sum,calc);
  ierr = MPI_Finalize();
}
```

# Example

Fortran

```
program sum2all
  include 'mpif.h'

  icomm = MPI_COMM_WORLD
  knt = 1
  call mpi_init(ierr)
  call mpi_comm_rank(icomm,mype,ierr)
  call mpi_comm_size(icomm,npes,ierr)
  val = dble(mype)

  call mpi_allreduce(val,sum,knt,MPI_REAL8,MPI_SUM,icomm,ierr)

  ncalc=(npes-1 + mod(npes,2))*(npes/2)
  print*,' pe#, sum, calc. sum = ',mype,sum,ncalc
  call mpi_finalize(ierr)
end
```



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# Compiling MPI Programs

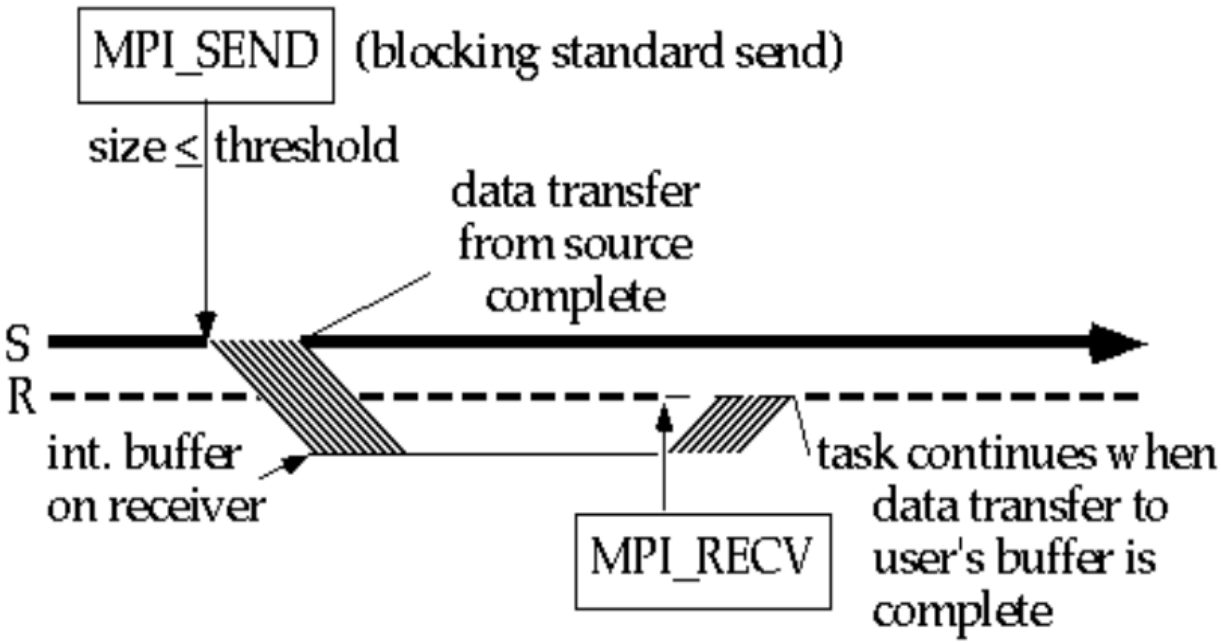
- Generally use a special compiler or compiler wrapper script
  - not defined by the standard
  - consult your implementation
  - handles correct include path, library path, and libraries
- MPICH-style (the most common)
  - `mpicc -o foo foo.c`
  - `mpif77 -o foo foo.f`

# Running MPI Programs

- MPI programs require some help to get started
  - what computers should I run on?
  - how do I access them?
- MPICH-style
  - `mpirun -np 10 -machinefile mach ./foo`
- When batch schedulers are involved, all bets are off
- On Ranger
  - `ibrun ./foo`
    and the scheduler handles the rest
- On Saguaro
  - create a jobscript that calls mpirun somewhere
  - `qsub ./jobscript`

# Blocking Send / Receive

- MPI_Send, does not return until buffer is safe to reuse: either when buffered, or when actually received. (implementation / runtime dependent)
- Rule of thumb: send completes only if receive is posted



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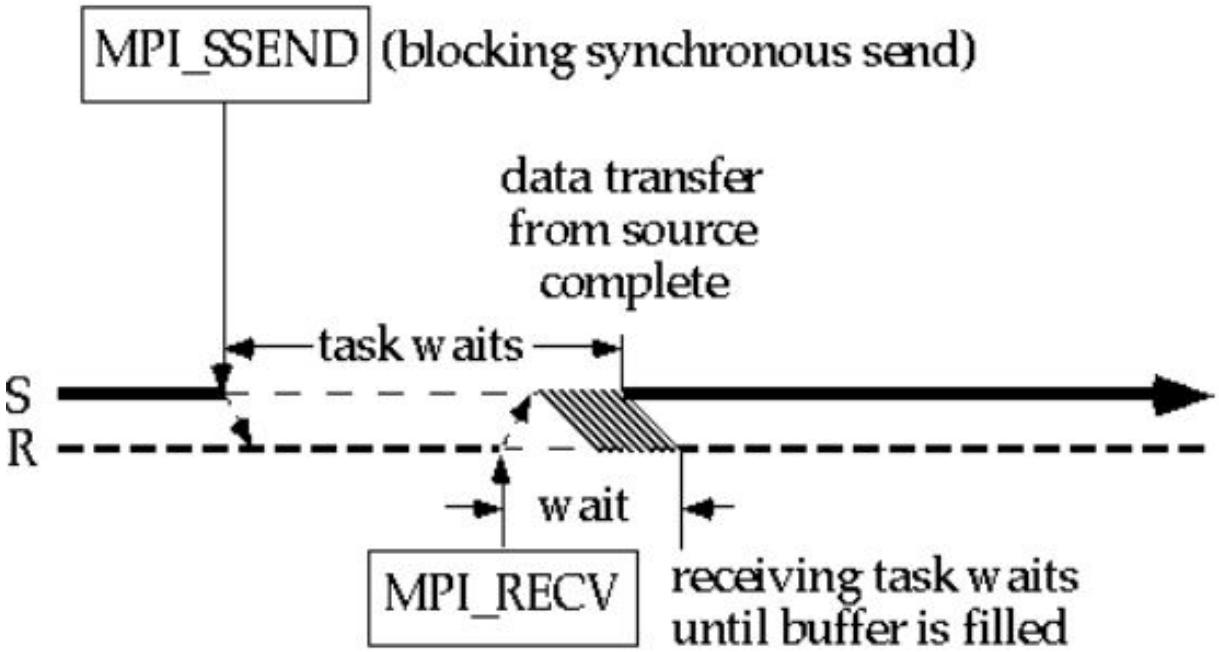
# Blocking Send / Receive

## Synchronous Mode

**MPI_Ssend**, which does not return until matching receive has been posted (non-local operation).



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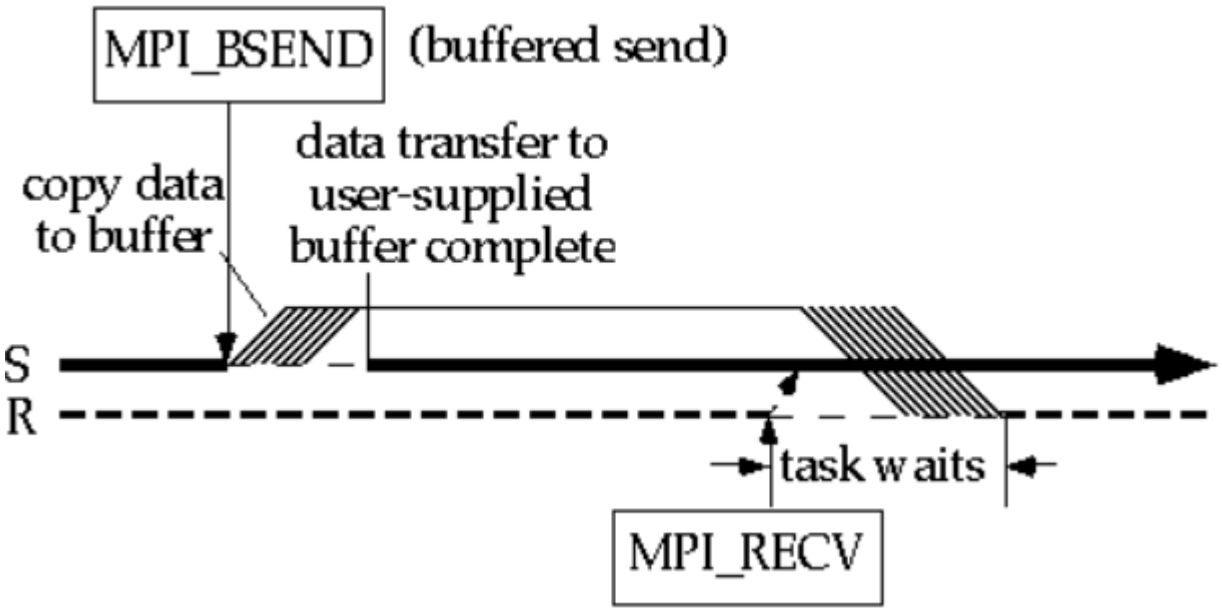
# Blocking Send / Receive

## Buffered Mode

**MPI_Bsend**, which completes as soon as the message buffer is copied into user-provided buffer



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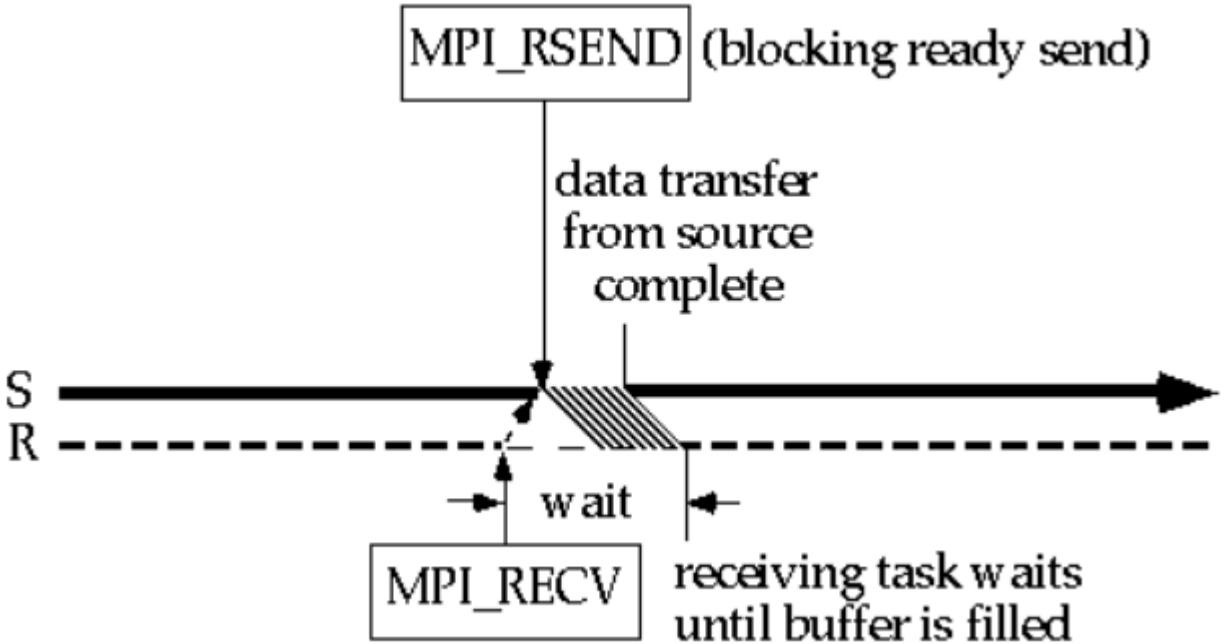
# Blocking Send / Receive

## Ready Mode

MPI_Rsend returns immediately assuming that a matching receive has been posted




Deadlocks occur when all tasks are waiting for events that haven't been initiated yet. It's most common with blocking communication.

# Blocking Send / Receive

- **Ready Mode** has least total overhead. However the assumption is that receive is already posted.
- **Synchronous mode** is portable and âĂIJsafeâĂİ. It does not depend on order (ready mode) or buffer space (buffered mode). However it incurs substantial overhead.
- **Buffered mode** decouples sender from receiver. No sync. overhead on sending task and order of execution does not matter (ready mode). User can control size of message buffers and total amount of space. However additional overhead may be incurred by copy to buffer and buffer space can run out.
- **Standard Mode** is implementation dependent. Small messages are generally buffered (avoiding sync. overhead) and large messages are usually sent synchronously (avoiding the required buffer space)



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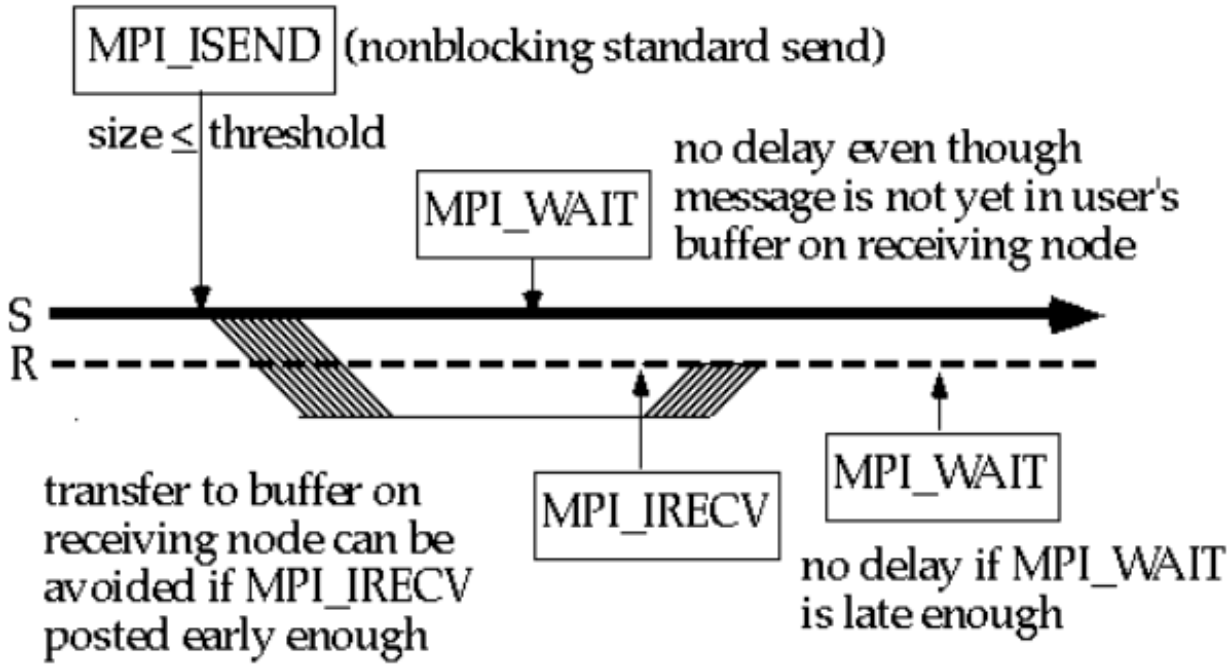
# Non-Blocking Send / Receive

- Nonblocking communication: calls return, system handles buffering
- MPI_Isend, completes immediately but user must check status before using the buffer for same (tag/receiver) send again; buffer can be reused for different tag/receiver.
- MPI_Irecv, gives a user buffer to the system; requires checking whether data has arrived.



# The Sendrecv Operation

## MPI_Sendrecv

- both in one call, source and dest can be the same
- Example 1: exchanging data with one other node; target and source the same
- Example 2: chain of processors
  - Operate on data
  - Send result to next processor, and receive next input from previous processor in line

Example

```
MPI_SENDRECV(
   sendbuf, sendcount, sendtype, dest, sendtag,
   recvbuf, recvcount, recvtype, source, recvtag,
   comm, status)
```



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# Advanced Collective Communication

- MPI_{Scatter,Gather,Allscatter,Allgather}v
- What does v stand for?
  - varying size, relative location of messages
- Advantages
  - more flexibility
  - less need to copy data into temp. buffers
  - more compact
- Disadvantage
  - Somewhat harder to program (more bookkeeping)



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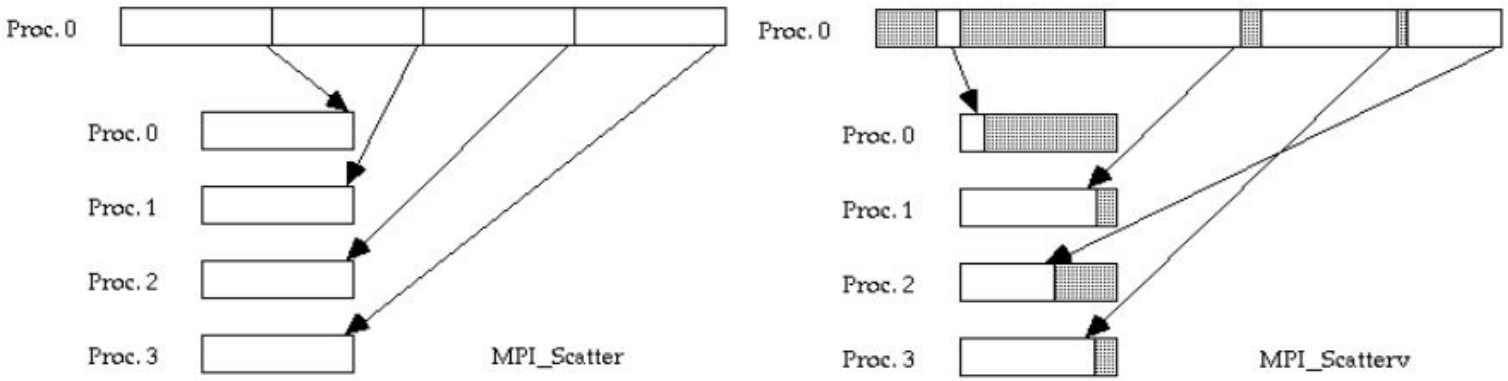
# Scatter vs Scatterv




Example

```
CALL mpi_scatterv(SENDBUF, SENDCOUNTS, DISPLS, SENDTYPE,
        RECVBUF, RECVCOUNTS, RECVTYPE, ROOT, COMM, IERR)
```

- SENDCOUNTS(i) is the number of items of type SENDTYPE to send from process ROOT to process i. Defined on ROOT.
- DISPLS(i) is the displacement from SENDBUF to the beginning of the i-th message, in units of SENDTYPE. Defined on ROOT.



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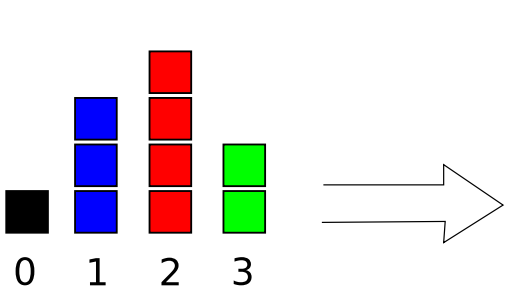
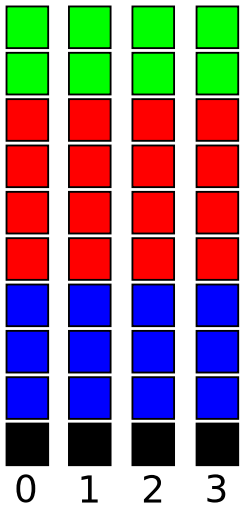
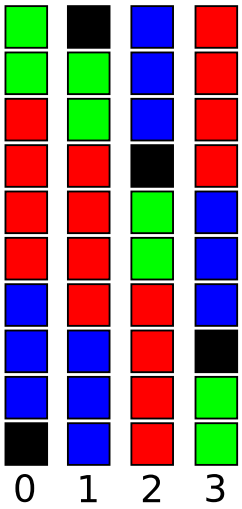
# Allgatherv Example




AllgatherV takes data of varied length from each task and distributes it to all tasks.




AllgatherV can also alter the order of data based on task.




Example

```
MPI_Allgatherv(
    void *sendbuf, int sendcount, MPI_Datatype sendtype,
    void *recvbuf, int *recvcounts, int *displs,
    MPI_Datatype recvtype, MPI_Comm comm )
```



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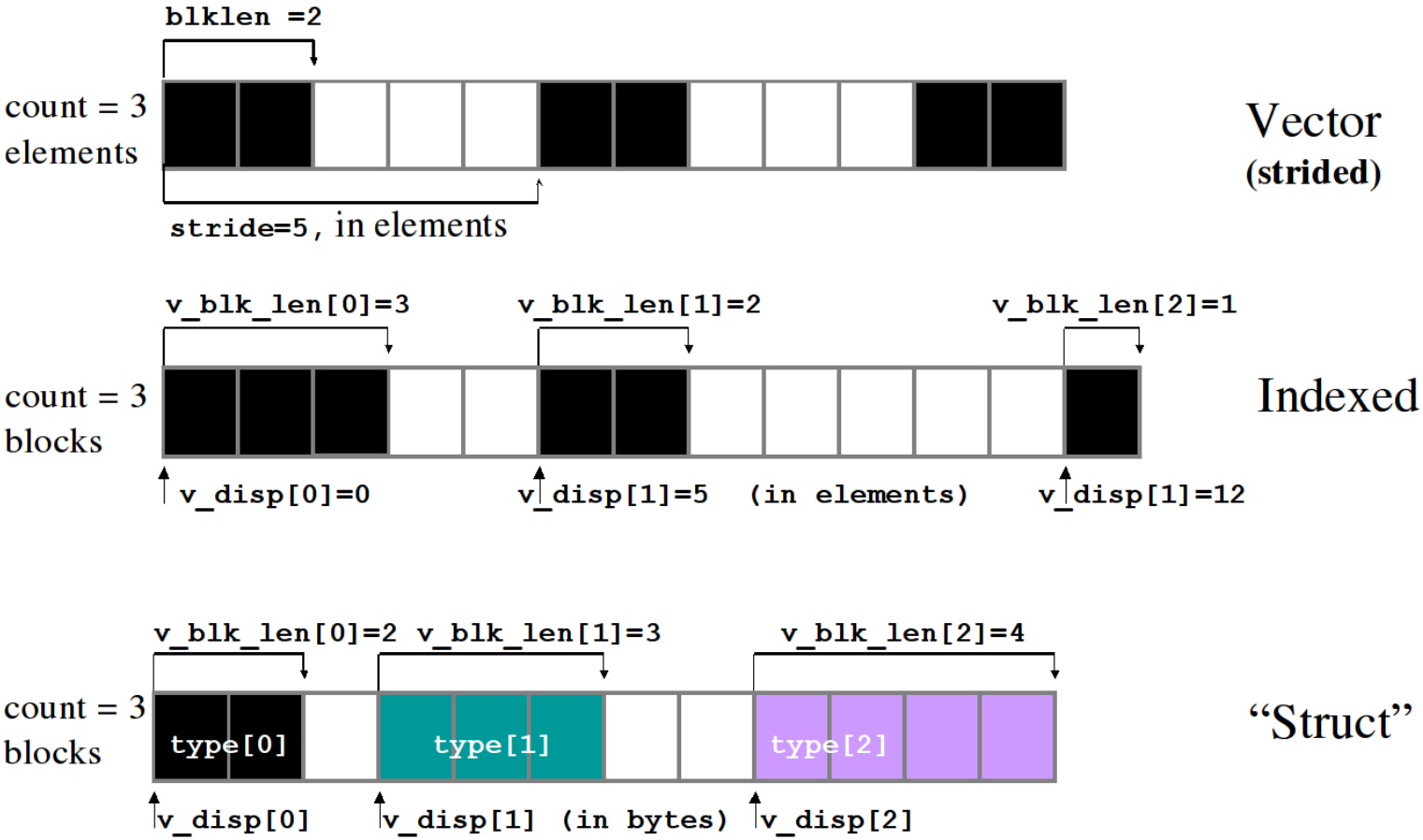
# Derived Datatypes

- MPI basic data-types are predefined for contiguous data of single type
- What if application has data of mixed types, or non-contiguous data?
  - existing solutions of multiple calls or copying into buffer and packing etc. are slow, clumsy and waste memory
  - better solution is creating/deriving datatypes for these special needs from existing datatypes
- Derived Data-types can be created recursively and at run-time
- Automatic packing and unpacking

# Types

- Elementary: Language-defined types
- Contiguous: Vector with stride of one
- Vector: Separated by constant 'stride'
- Hvector: Vector, with stride in bytes
- Indexed: Array of indices (for scatter/gather)
- Hindexed: Indexed, with indices in bytes
- Struct: General mixed types (for C structs etc.)

# Types


blklen =2
count = 3
elements
stride=5, in elements
Vector
(strided)
v_blk_len[0]=3
v_blk_len[1]=2
v_blk_len[2]=1
count = 3
blocks
v_disp[0]=0
v_disp[1]=5 (in elements)
v_disp[1]=12
Indexed
v_blk_len[0]=2
v_blk_len[1]=3
v_blk_len[2]=4
count = 3
blocks
type[0]
type[1]
type[2]
v_disp[0]
v_disp[1] (in bytes)
v_disp[2]
"Struct"

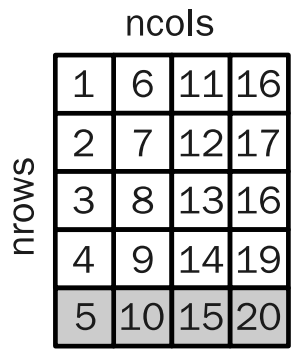
# Sending a Row in Fortran

## MPI_Type_vector

Allows creating non-contiguous vectors with constant stride

Syntax

```
mpi_type_vector(count, blocklen, stride,
                oldtype, vtype, ierr)
mpi_type_commit(vtype, ierr)
```




Example

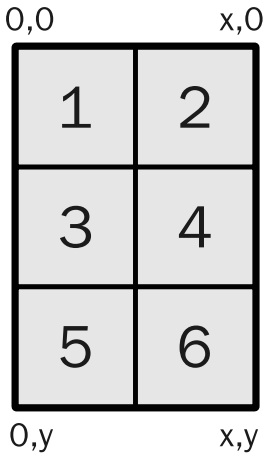
```
call MPI_Type_vector(ncols, 1, nrows,
                     MPI_DOUBLE_PRECISION, vtype, ierr)
call MPI_Type_commit(vtype, ierr)
call MPI_Send( A(nrows,1) , 1 , vtype )
```

# Communicators and Groups

- All MPI communication is relative to a communicator which contains a context and a group.
- The group is just a set of processes.
- Groups can be created by using the union, difference, intersection, and range operations.

## Data Decomposition

How can we construct a communicator with a 2D decomposition? For example: X by Y and 6 processor elements



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## MPI-1 Standard

http://www.mpi-forum.org/docs/mpi-11-html/mpi-report.html

## MPI-2 Standard

http://www.mpi-forum.org/docs/mpi-20-html/mpi2-report.htm

## MPI Guides

http://www.clustermonkey.net/content/category/5/13/28/

# Thank you!