MPI (Message Passing Interface)

- Developed and maintained by a large consortium of industry, academic, and government contributors
- De facto message passing standard for parallel computing
- Language bindings for C and Fortran (and formerly C++)
  - The C interface can still be used from C++
- Available on virtually all platforms; both proprietary and open source (MPICH, OpenMPI) versions
  - [‘CH’ for Chameleon, the underlying communication library of the original MPICH implementation.]
- Grew out of an earlier message passing system, PVM (Parallel Virtual Machine), no longer actively maintained.
  - MPI-2 subsumed all significant PVM functionality.
  - Current version (2023) is MPI-5.

Compiling and Running

- `mpiCC -o myprog myprog.cpp`
- `mpiexec [-n 16] [-configfile foo] ./myprog <args>`
- Creates specified number of Unix processes, on nodes listed in the specified file
  - Watch Blackboard for more detailed instructions

MPI Process Creation/Destruction

`MPI_Init(int *argc, char ***argv)`

Initializes the MPI execution environment.

(Note the extra level of indirection.)

`MPI_Finalize(void)`

Terminates MPI execution environment. If you forget to make all processes call this routine, you may leave orphans on the system (run ps on all nodes to find them).

MPI Process Identification

`MPI_Comm_size(comm, &size)`

Determines the number of processes

`MPI_Comm_rank(comm, &pid)`

`pid` is the process identifier of the caller

(consecutive ints, starting with 0)

`comm` is typically `MPI_COMM_WORLD` — all processes in the program.

NB: by default the program dies if any call fails; return values can safely be ignored in C and C++.

MPI Basic Send

```
MPI_Send(buf, count, datatype, dest, tag, comm)
```

`buf`: address of send buffer

`count`: number of elements

`datatype`: data type of send buffer elements
    (built-in or user-defined)

`dest`: process id (rank) of destination process

`tag`: message tag (ignore for now)

`comm`: communicator (e.g., `MPI_COMM_WORLD`)

MPI Basic Receive

```
MPI_Recv(buf, count, datatype, source, tag, comm,
          &status)
```

`buf`: address of receive buffer

`count`: size of receive buffer in elements

`datatype`: data type of receive buffer elements

`source`: source process rank or `MPI_ANY_SOURCE`

`tag` and `comm`: ignore for now

`status`: status object (indicates sender and tag)

MPI Matrix Multiply (initial version, in C)

```
int me, p;  const int N = …
int (*a)[N], (*b)[N], (*c)[N];
int main(int argc, char *argv[])
{
  MPI_Init (&argc, &argv);
  MPI_Comm_rank(MPI_COMM_WORLD, &me);
  MPI_Comm_size(MPI_COMM_WORLD, &p);
  // malloc space for a, b, and c
  // Data distribution ...
  // Computation ...
  // Result gathering ...
  MPI_Finalize();
}
```

MPI Matrix Multiply (initial version)

```
/* Data distribution */
  if (me == 0) {
    for (i = 1; i < p; i++) {
      // assume p divides N evenly
      MPI_Send(&a[i*N/p][0], N*N/p, MPI_INT, i, 0,
               MPI_COMM_WORLD);
        // stripe of a, all of b
      MPI_Send(b, N*N, MPI_INT, i, 0, MPI_COMM_WORLD);
    }
  } else {
    MPI_Recv(&a[me*N/p][0], N*N/p, MPI_INT, 0, 0,
             MPI_COMM_WORLD, 0);
    MPI_Recv(b, N*N, MPI_INT, 0, 0, MPI_COMM_WORLD, 0);
  }
```

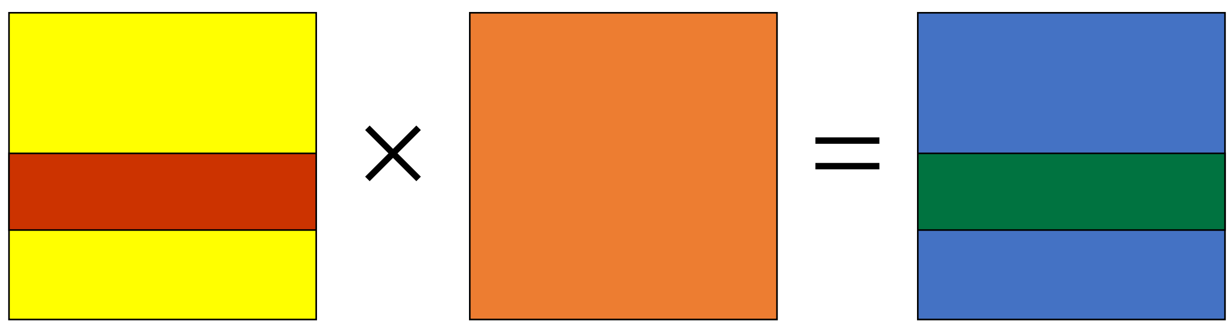
MPI Matrix Multiply (initial version)

```
/* Computation */
  for (i = me*N/p; i < (me+1)*N/p; i++) {
    for (j = 0; j < N; j++) {
      c[i][j] = 0;
      for (k = 0; k < N; k++) {
        c[i][j] += a[i][k] * b[k][j];
      }
    }
  }
```

MPI Matrix Multiply (initial version)

```
/* Result gathering */
  if (me != 0) {
    MPI_Send(&c[me*N/p][0], N*N/p, MPI_INT, 0, 0,
             MPI_COMM_WORLD);
  } else {
    for (i = 1; i < p; i++) {
      MPI_Recv(&c[i*N/p][0], N*N/p, MPI_INT, i, 0,
               MPI_COMM_WORLD, 0);
    }
  }
```

Work Performed by One Process



A B C

We don't send the unused portions of A and C.
Why reserve space for them?

MPI Matrix Multiply (with index renaming)

NB: if `me != 0`, `a` is malloc-ed smaller in this example

```
/* Data distribution */
  if (me == 0) {
    for (i = 1; i < p; i++) {
      MPI_Send(&a[i*N/p][0], N*N/p, MPI_INT, i, 0,
                MPI_COMM_WORLD);
      MPI_Send(b, N*N, MPI_INT, i, 0, MPI_COMM_WORLD);
    }
  } else {
    MPI_Recv(a, N*N/p, MPI_INT, 0, 0, MPI_COMM_WORLD, 0);
    MPI_Recv(b, N*N, MPI_INT, 0, 0, MPI_COMM_WORLD, 0);
  }
```

MPI Matrix Multiply (with index renaming)

```
/* Computation */
  for (i = 0; i < N/p; i++) {
    for (j = 0; j < N; j++) {
      c[i][j] = 0;
      for (k = 0; k < N; k++) {
        c[i][j] += a[i][k] * b[k][j];
      }
    }
  }
```

MPI Matrix Multiply (with index renaming)

```
/* Result gathering */
  if (me != 0) {
    MPI_Send(c, N*N/p, MPI_INT, 0, 0, MPI_COMM_WORLD);
  } else {
    for (i = 1; i < p; i++) {
      MPI_Recv(&c[i*N/p][0], N*N/p, MPI_INT, i, 0,
               MPI_COMM_WORLD, 0);
    }
  }
```

Global Operations (1 of 2)

- So far, we have only looked at point-to-point or one-to-one message passing facilities.
- Often, it is useful to have one-to-many or many-to-one message communication.
- This is what MPI's global operations do.

Global Operations (2 of 2)

- `MPI_Barrier`
- `MPI_Bcast`
- `MPI_Scatter`
- `MPI_Gather`
- `MPI_Allgather`
- `MPI_Alltoall`
- `MPI_Reduce`
- `MPI_Allreduce`

Barrier

`MPI_Barrier(comm)`

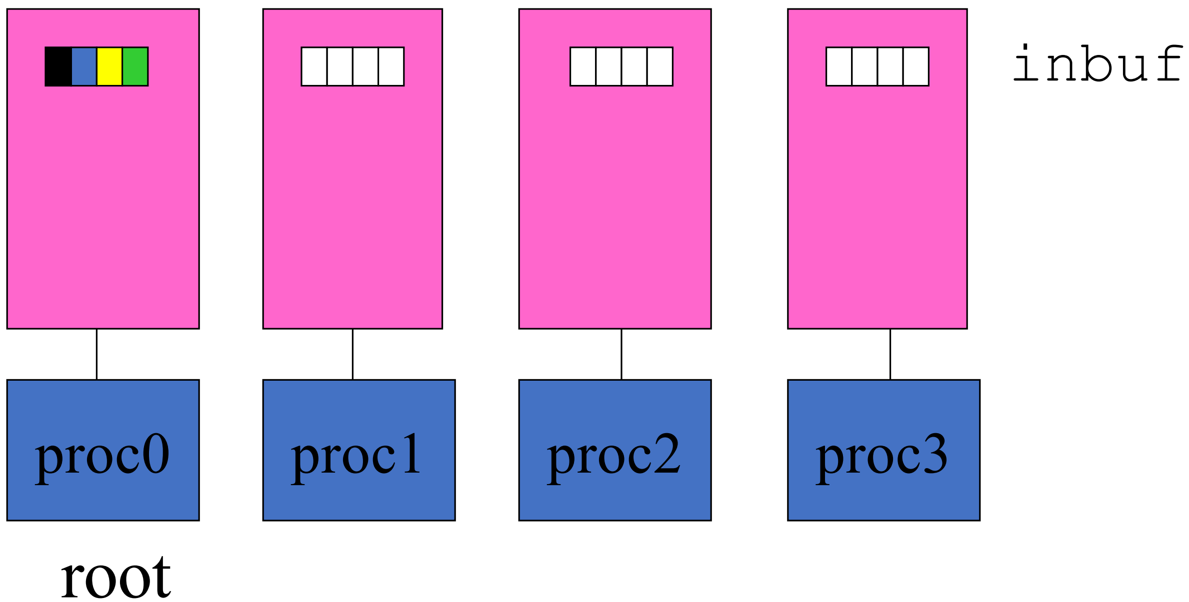
Global barrier synchronization, as with shared memory: all processes wait until all have arrived.

Broadcast

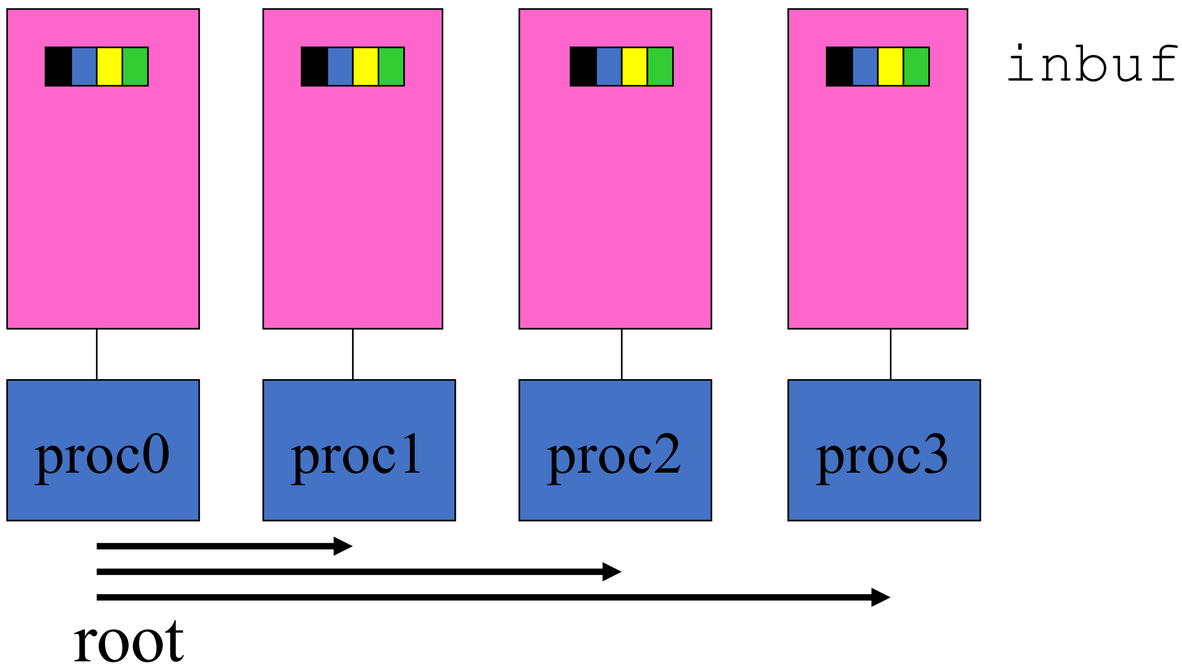
`MPI_Bcast(inbuf, incnt, intype, root, comm)`

- `inbuf`: address of input buffer (on root);
  address of output buffer (elsewhere)
- `incnt`: number of elements
- `intype`: type of elements
- `root`: rank of root (sender) process

Before Broadcast



After Broadcast

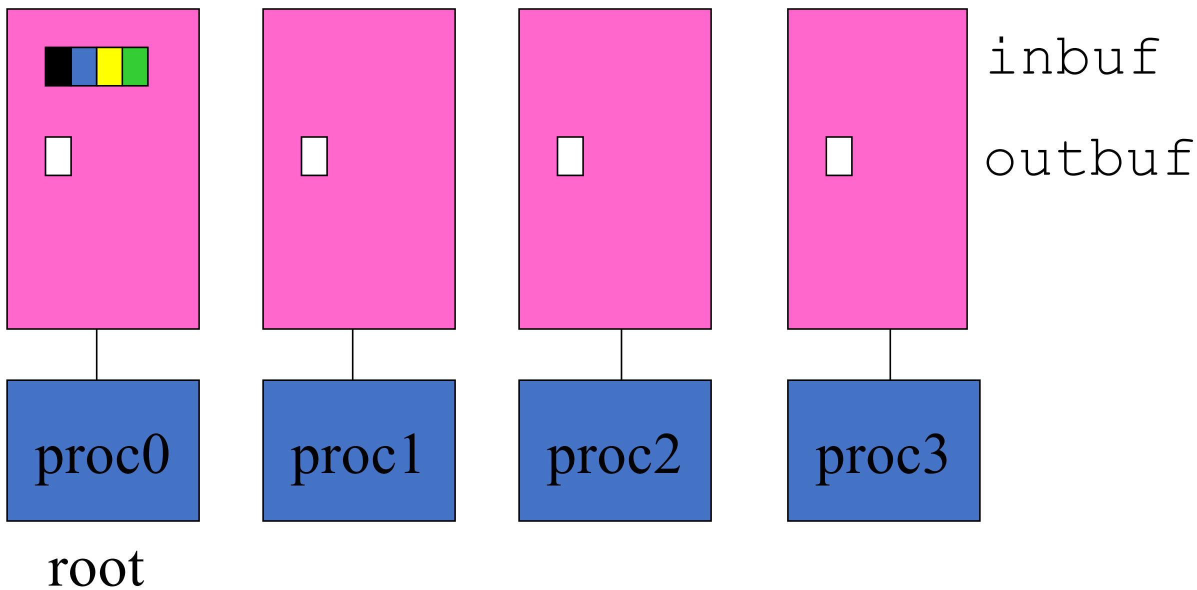


Scatter

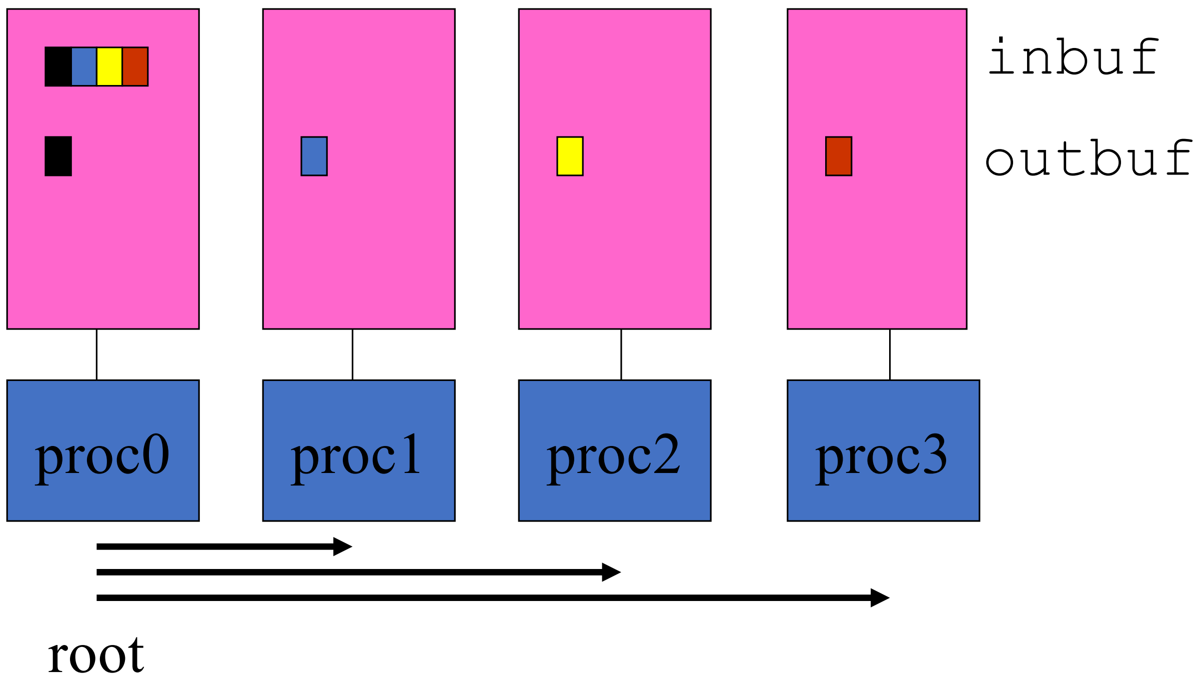
```
MPI_Scatter(inbuf, incnt, intype, outbuf,
            outcnt, outtype, root, comm)
```

- `inbuf`: address of input buffer (on root)
- `incnt`: number of elements sent to each process
- `intype`: type of input elements
- `outbuf`: address of output buffer (on non-root)
- `outcnt`: num. elements received by each process
- `outtype`: type of output elements (usually = `intype`)
- `root`: rank of root process

Before Scatter



After Scatter

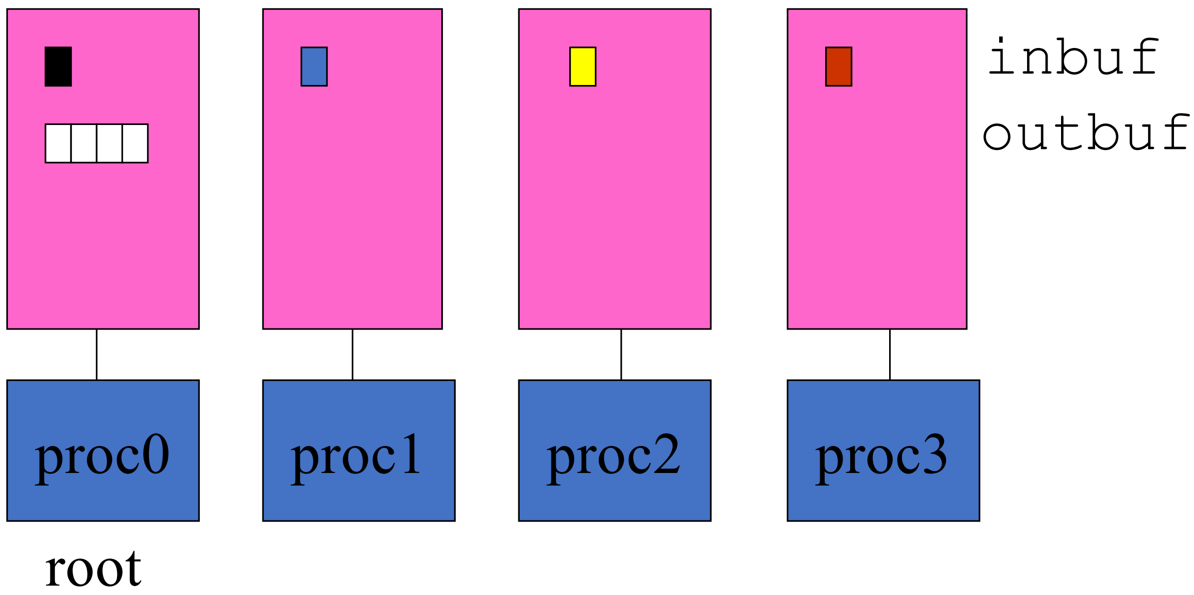


Gather

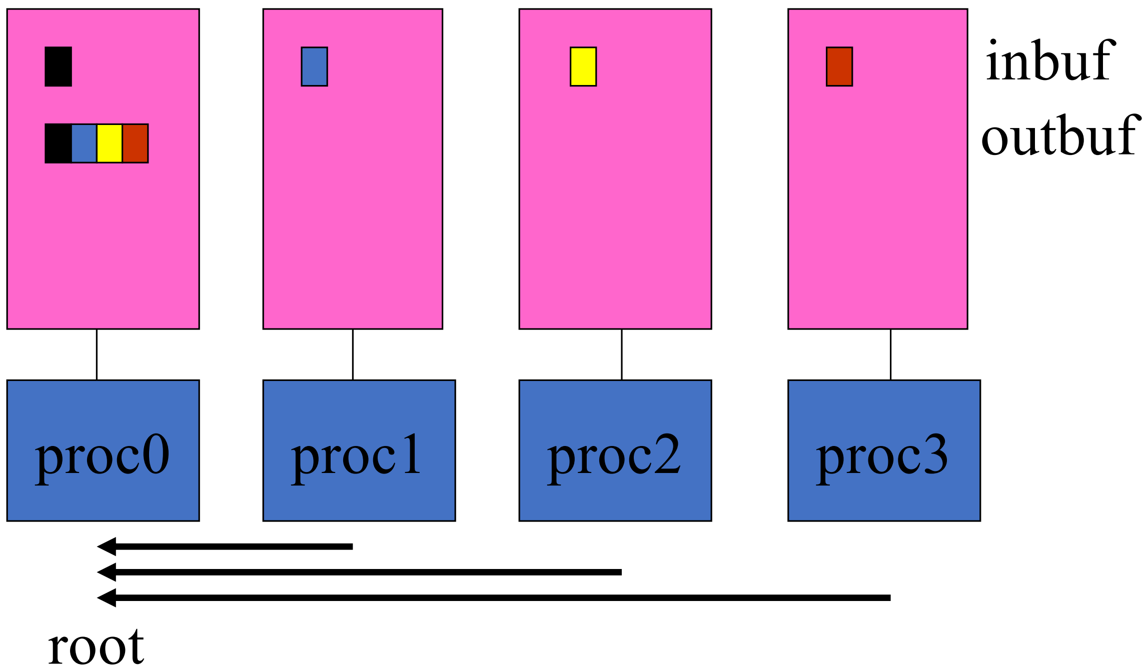
```
MPI_Gather(inbuf, incnt, intype, outbuf, outcnt,
           outtype, root, comm)
```

- `inbuf`: address of input buffer
- `incnt`: number of input elements
- `intype`: type of input elements
- `outbuf`: address of output buffer
- `outcnt`: number of output elements
- `outtype`: type of output elements
- `root`: rank of root process

Before Gather



After Gather



MPI Matrix Multiply with index renaming and scatter/gather

```
main(int argc, char *argv[]) {
  MPI_Init(&argc, &argv);
  MPI_Comm_rank(MPI_COMM_WORLD, &me);
  MPI_Comm_size(MPI_COMM_WORLD, &p);
  MPI_Scatter(a, N*N/p, MPI_INT, a, N*N/p, MPI_INT, 0,
              MPI_COMM_WORLD);  // assume N%p == 0
  MPI_Bcast(b, N*N, MPI_INT, 0, MPI_COMM_WORLD);
  ...
```

MPI Matrix Multiply with index renaming and scatter/gather

```
  for (i = 0; i < N/p; i++) {
    for (j = 0; j < N; j++) {
      c[i][j] = 0;
      for (k = 0; k < N; k++) {
        c[i][j] += a[i][k] * b[k][j];
      }
    }
  MPI_Gather(c, N*N/p, MPI_INT, c, N*N/p,
             MPI_INT, 0, MPI_COMM_WORLD);
  MPI_Finalize();
}
```

Additional Features

- Nonblocking communication
- “One-sided” communication
  - Essentially remote reads and writes
- User-defined datatypes
- Nontrivial communicators
- Parallel I/O
- User-Level Fault Mitigation (ULFM) — mechanisms to detect and recover from individual process failures