Introduction to Programming by MPI for Parallel FEM Report S1 & S2 in C

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Motivation for Parallel Computing (and this class)

- Large-scale parallel computer enables fast computing in large-scale scientific simulations with detailed models. Computational science develops new frontiers of science and engineering.
- Why parallel computing ?
  - faster & larger
  - “larger” is more important from the view point of “new frontiers of science & engineering”, but “faster” is also important.
  - + more complicated
  - Ideal: Scalable
    - Solving N^x scale problem using N^x computational resources during same computation time.

Scalable, Scaling, Scalability

- Solving N^x scale problem using N^x computational resources during same computation time
  - for large-scale problems: **Weak Scaling, Weak Scalability**
  - e.g. CG solver: more iterations needed for larger problems
- Solving a problem using N^x computational resources during 1/N computation time
  - for faster computation: **Strong Scaling, Strong Scalability**

Overview

- What is MPI ?
- Your First MPI Program: Hello World
- Collective Communication
- Point-to-Point Communication

What is MPI ? (1/2)

- Message Passing Interface
- “Specification” of message passing API for distributed memory environment
  - Not a program, Not a library
    - http://www.mcs.anl.gov/mpi/www/
- History
  - 1992 MPI Forum
  - 1994 MPI-1
  - 1997 MPI-2: MPI I/O
  - 2012 MPI-3: Fault Resilience, Asynchronous Collective
- Implementation
  - mpich ANL (Argonne National Laboratory), OpenMPI, MVAPICH
  - H/W vendors
  - C/C++, FOTRAN, Java ; Unix, Linux, Windows, Mac OS

What is MPI ? (2/2)

- “mpich” (free) is widely used
  - supports MPI-2 spec. (partially)
  - MPICH2 after Nov. 2005.
  - http://www.mcs.anl.gov/mpi/
- Why MPI is widely used as *de facto standard ?*
  - Uniform interface through MPI forum
    - Portable, can work on any types of computers
    - Can be called from Fortran, C, etc.
  - mpich
    - free, supports every architecture
- PVM (Parallel Virtual Machine) was also proposed in early 90’s but not so widely used as MPI

References

- W.Gropp et al., Using MPI second edition, MIT Press, 1999.
- M.J.Quinn, Parallel Programming in C with MPI and OpenMP, McGrawhill, 2003.
- W.Gropp et al., MPI：The Complete Reference Vol.I, II, MIT Press, 1998.
- http://www.mcs.anl.gov/mpi/www/
  - API (Application Interface) of MPI

How to learn MPI (1/2)

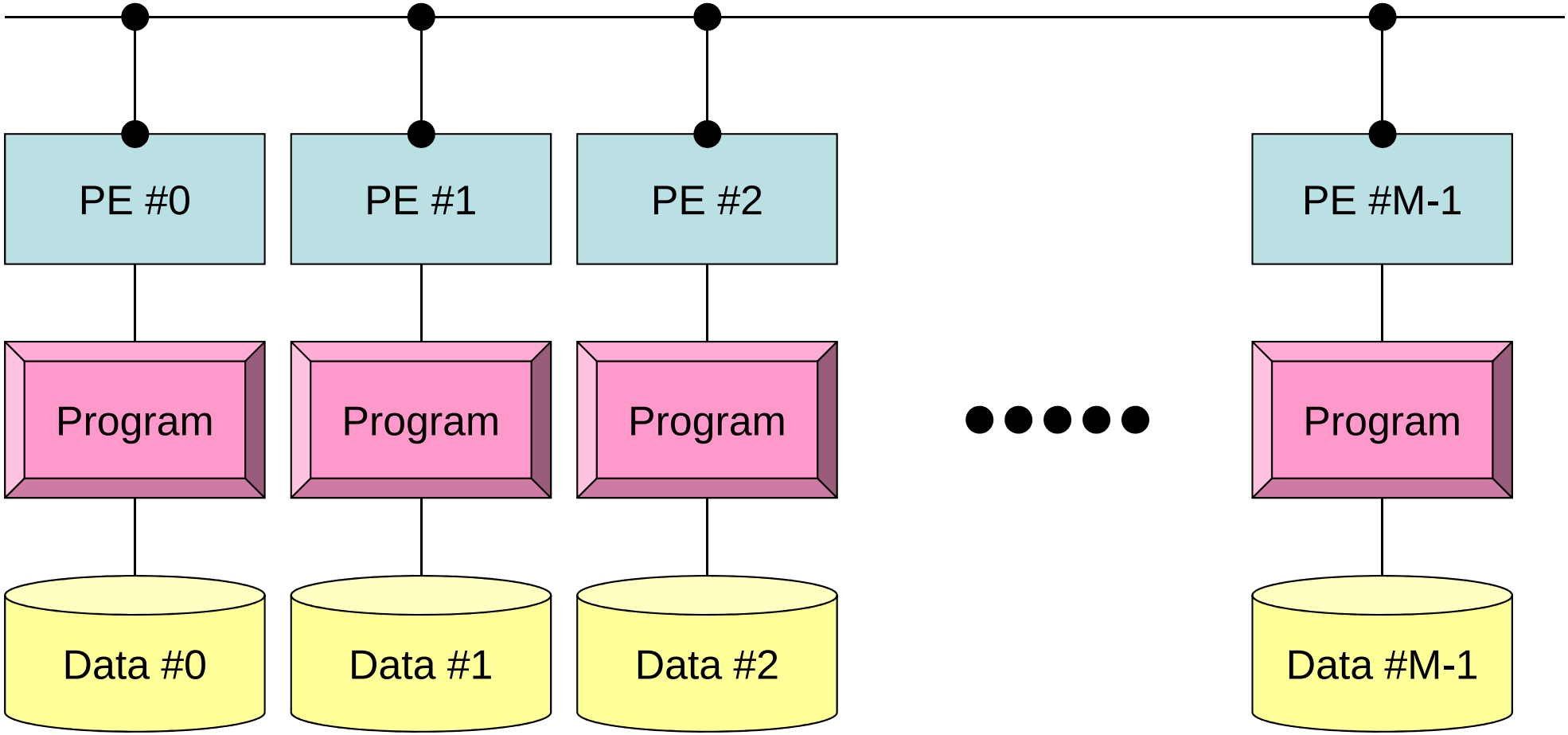
- Grammar
  - 10-20 functions of MPI-1 will be taught in the class
    - although there are many convenient capabilities in MPI-2
  - If you need further information, you can find information from web, books, and MPI experts.
- Practice is important
  - Programming
  - “Running the codes” is the most important
- Be familiar with or “grab” the idea of SPMD/SIMD op’s
  - Single Program/Instruction Multiple Data
  - Each process does same operation for different data
    - Large-scale data is decomposed, and each part is computed by each process
  - Global/Local Data, Global/Local Numbering

PE: Processing Element
Processor, Domain, Process

SPMD

You understand 90% MPI, if you understand this figure.

```
mpirun -np M <Program>
```



Each process does same operation for different data

Large-scale data is decomposed, and each part is computed by each process

It is ideal that parallel program is not different from serial one except communication.

Some Technical Terms

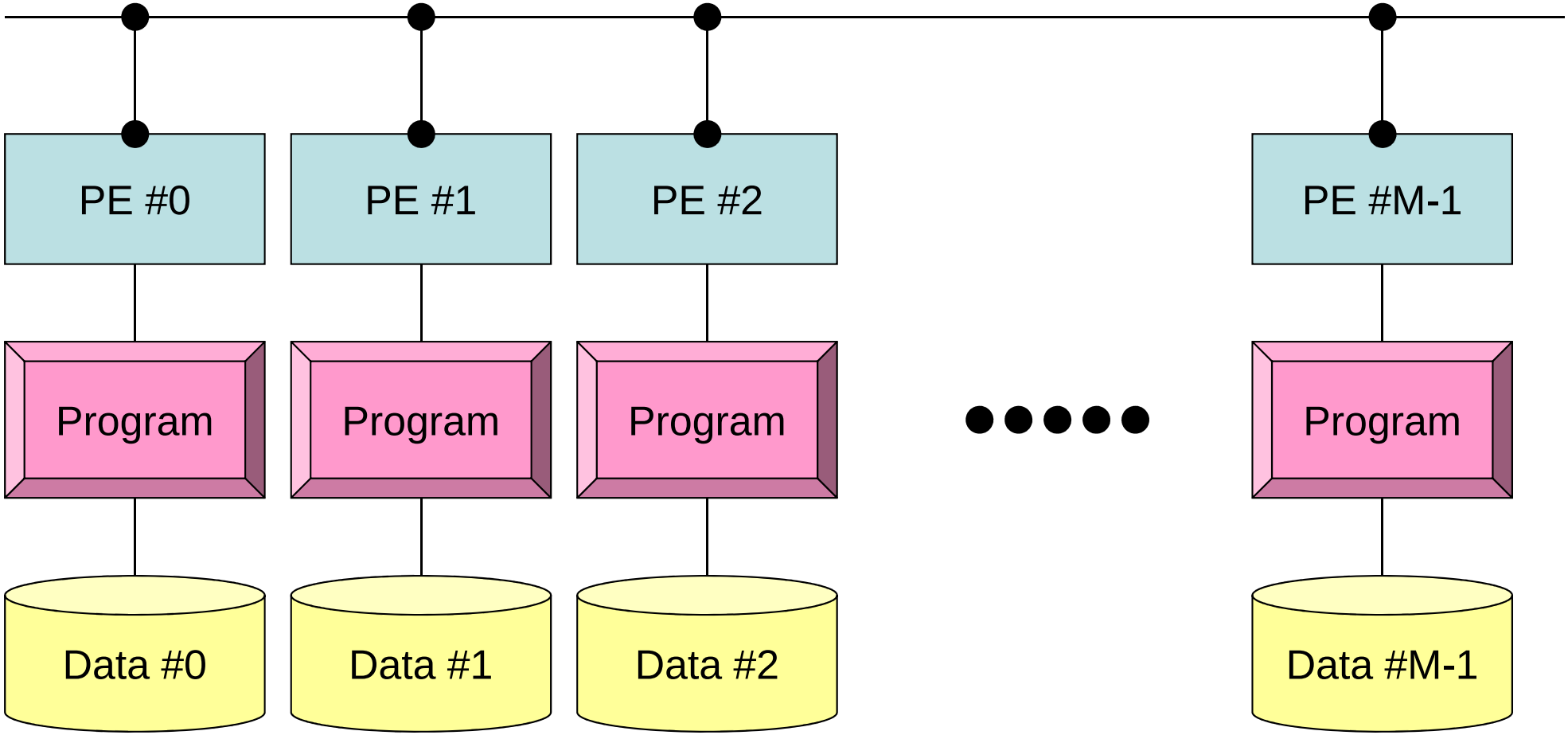
- Processor, Core
  - Processing Unit (H/W), Processor=Core for single-core proc's
- Process
  - Unit for MPI computation, nearly equal to "core"
  - Each core (or processor) can host multiple processes (but not efficient)
- PE (Processing Element)
  - PE originally mean "processor", but it is sometimes used as "process" in this class. Moreover it means "domain" (next)
    - In multicore proc's: PE generally means "core"
- Domain
  - domain=process (=PE), each of "MD" in "SPMD", each data set
- Process ID of MPI (ID of PE, ID of domain) starts from "0"
  - if you have 8 processes (PE's, domains), ID is 0~7

PE: Processing Element
Processor, Domain, Process

SPMD

You understand 90% MPI, if you understand this figure.

```
mpirun -np M <Program>
```



Each process does same operation for different data

Large-scale data is decomposed, and each part is computed by each process

It is ideal that parallel program is not different from serial one except communication.

How to learn MPI (2/2)

- NOT so difficult.
- Therefore, 2-3 lectures are enough for just learning grammar of MPI.

- Grab the idea of SPMD !

Schedule

- MPI
  - Basic Functions
  - Collective Communication
  - Point-to-Point (or Peer-to-Peer) Communication

- 105 min. x 3-4 lectures
  - Collective Communication
    - Report S1
  - Point-to-Point Communication
    - Report S2: Parallelization of 1D code
  - At this point, you are almost an expert of MPI programming.

- What is MPI ?
- **Your First MPI Program: Hello World**
- Collective Communication
- Point-to-Point Communication

Login to Reedbush-U

```
ssh t18**@reedbush.cc.u-tokyo.ac.jp
```

Create directory

```
>$ cd /lustre/gt18/t18XXX    or    cdw
>$ mkdir pFEM (your favorite name)
>$ cd pFEM
```

In this class this top-directory is called `<$O-TOP>`.
Files are copied to this directory.

Under this directory, `S1, S2, S1-ref` are created:

```
<$O-S1> = <$O-TOP>/mpi/S1
<$O-S2> = <$O-TOP>/mpi/S2
```

Reedbush-U

ECCS2016

Copying files on Reedbush-U

Fortan

```
>$ cd /lustre/gt18/gt18XXX/pFEM
>$ cp /lustre/gt00/z30088/class_eps/F/s1-f.tar .
>$ tar xvf s1-f.tar
```

C

```
>$ cd /lustre/gt18/gt18XXX/pFEM
>$ cp /lustre/gt00/z30088/class_eps/C/s1-c.tar .
>$ tar xvf s1-c.tar
```

Confirmation

```
>$ ls
   mpi

>$ cd mpi/S1
```

This directory is called as <$O-S1>.

<$O-S1> = <$O-TOP>/mpi/S1

First Example

hello.f

```
implicit REAL*8 (A-H,O-Z)
include 'mpif.h'
integer :: PETOT, my_rank, ierr

call MPI_INIT      (ierr)
call MPI_COMM_SIZE (MPI_COMM_WORLD, PETOT, ierr )
call MPI_COMM_RANK (MPI_COMM_WORLD, my_rank, ierr )

write (*,'(a,2i8)') 'Hello World FORTRAN', my_rank, PETOT

call MPI_FINALIZE (ierr)

stop
end
```

hello.c

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

Compiling hello.f/c

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1
>$ mpiifort -O3 hello.f
>$ mpicc -O3 hello.c
```

FORTRAN

$> "mpiifort":
required compiler & libraries are included for FORTRAN90+MPI

C

$> "mpicc":
required compiler & libraries are included for C+MPI

Running Job

- Batch Jobs
  - Only batch jobs are allowed.
  - Interactive executions of jobs are not allowed.
- How to run
  - writing job script
  - submitting job
  - checking job status
  - checking results
- Utilization of computational resources
  - 1-node (36 cores) is occupied by each job.
  - Your node is not shared by other jobs.

Job Script

- **<$O-S1>/hello.sh**
- Scheduling + Shell Script

```
#!/bin/sh
#PBS -q u-lecture8                    Name of "QUEUE"
#PBS -N HELLO                         Job Name
#PBS -l select=1:mpiprocs=4           node#, MPI proc#/node
#PBS -Wgroup_list=gt18                Group Name (Wallet)
#PBS -l walltime=00:05:00             Computation Time
#PBS -e err                           Standard Error
#PBS -o hello.lst                     Standard Outpt

cd $PBS_O_WORKDIR                     go to current dir
. /etc/profile.d/modules.sh           (ESSENTIAL)
export I_MPI_PIN_DOMAIN=socket        Execution on each socket
export I_MPI_PERHOST=4                =mpiprocs, stable
mpirun ./impimap.sh ./a.out           Exec's
```

impimap.sh

NUMA: utilizing resource (e.g. memory) of the core where job is running: Performance is stable

```
#!/bin/sh
numactl --localalloc $@
```

Process Number

```
#PBS -l select=1:mpiprocs=4     1-node, 4-proc's
#PBS -l select=1:mpiprocs=16    1-node, 16-proc's
#PBS -l select=1:mpiprocs=36    1-node, 36-proc's
#PBS -l select=2:mpiprocs=32    2-nodes, 32x2=64-proc's
#PBS -l select=8:mpiprocs=36    8-nodes, 36x8=288-proc's
```

Job Submission

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1
>$ qsub hello.sh

>$ cat hello.lst

  Hello World 0
  Hello World 3
  Hello World 2
  Hello World 1
```

Available QUEUE's

- Following 2 queues are available.
- 8 nodes can be used
  - **`u-lecture`**
    - 8 nodes (288 cores), 10 min., valid until the end of November, 2018
    - Shared by all "educational" users
  - **`u-lecture8`**
    - 4 nodes (144 cores), 10 min., active during class time
    - More jobs (compared to **`lecture`**) can be processed up on availability.

Submitting & Checking Jobs

- Submitting Jobs `qsub SCRIPT NAME`
- Checking status of jobs `rbstat`
- Deleting/aborting `qdel JOB ID`
- Checking status of queues `rbstat --rsc`
- Detailed info. of queues `rbstat --rsc -x`
- Number of running jobs `rbstat -b`
- History of Submission `rbstat -H`
- Limitation of submission `rbstat --limit`

Basic/Essential Functions

```
implicit REAL*8 (A-H,O-Z)
include 'mpif.h'
integer :: PETOT, my_rank, ierr

call MPI_INIT      (ierr)
call MPI_COMM_SIZE (MPI_COMM_WORLD, PETOT, ierr )
call MPI_COMM_RANK (MPI_COMM_WORLD, my_rank, ierr )

write (*,'(a,2i8)') 'Hello World FORTRAN', my_rank, PETOT

call MPI_FINALIZE (ierr)

stop
end
```

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

`mpif.h', "mpi.h"

Essential Include file

"use mpi" is possible in F90

MPI_Init

Initialization

MPI_Comm_size

Number of MPI Processes

mpirun -np XX <prog>

MPI_Comm_rank

Process ID starting from 0

MPI_Finalize

Termination of MPI processes

Difference between FORTRAN/C

- (Basically) same interface
  - In C, UPPER/lower cases are considered as different
    - e.g.: **MPI_C**omm_size
      - MPI: UPPER case
      - First character of the function except “MPI_” is in UPPER case.
      - Other characters are in lower case.
- In Fortran, return value `ierr` has to be added at the end of the argument list.
- C needs special types for variables:
  - MPI_Comm, MPI_Datatype, MPI_Op etc.
- **`MPI_INIT`** is different:
  - `call MPI_INIT (ierr)`
  - `MPI_Init (int *argc, char ***argv)`

What's are going on ?

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;
    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

```
#!/bin/sh
#PBS -q u-lecture                    Name of "QUEUE"
#PBS -N HELLO                        Job Name
#PBS -l select=1:mpiprocs=4          node#, proc#/node
#PBS -Wgroup_list=gt29               Group Name (Wallet)
#PBS -l walltime=00:05:00            Computation Time
#PBS -e err                          Standard Error
#PBS -o hello.lst                    Standard Outpt

cd $PBS_O_WORKDIR                    go to current dir
. /etc/profile.d/modules.sh          (ESSENTIAL)
export I_MPI_PIN_DOMAIN=socket       Execution on each socket
mpirun ./impimap.sh ./a.out          Exec's
```

- **`mpirun`** starts up 4 MPI processes ("proc=4")
  - A single program runs on four processes.
  - each process writes a value of `myid`
- Four processes do same operations, but values of **`myid`** are different.
- Output of each process is different.
- That is SPMD !

mpi.h, mpif.h

```
implicit REAL*8 (A-H,O-Z)
include 'mpif.h'
integer :: PETOT, my_rank, ierr

call MPI_INIT      (ierr)
call MPI_COMM_SIZE (MPI_COMM_WORLD, PETOT, ierr )
call MPI_COMM_RANK (MPI_COMM_WORLD, my_rank, ierr )

write (*,'(a,2i8)') 'Hello World FORTRAN', my_rank, PETOT

call MPI_FINALIZE (ierr)

stop
end
```

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

- Various types of parameters and variables for MPI & their initial values.
- Name of each var. starts from “MPI_”
- Values of these parameters and variables cannot be changed by users.
- Users do not specify variables starting from “MPI_” in users’ programs.

C

MPI_Init

- Initialize the MPI execution environment (required)
- It is recommended to put this BEFORE all statements in the program.

- **MPI_Init (argc, argv)**

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

C

MPI_Finalize

- Terminates MPI execution environment (required)
- It is recommended to put this AFTER all statements in the program.
- Please do not forget this.

- **MPI_Finalize ()**

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

C

MPI_Comm_size

- Determines the size of the group associated with a communicator
- not required, but very convenient function

- **MPI_Comm_size (comm, size)**
  - **comm** MPI_Comm I communicator
  - **size** int O number of processes in the group of communicator

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

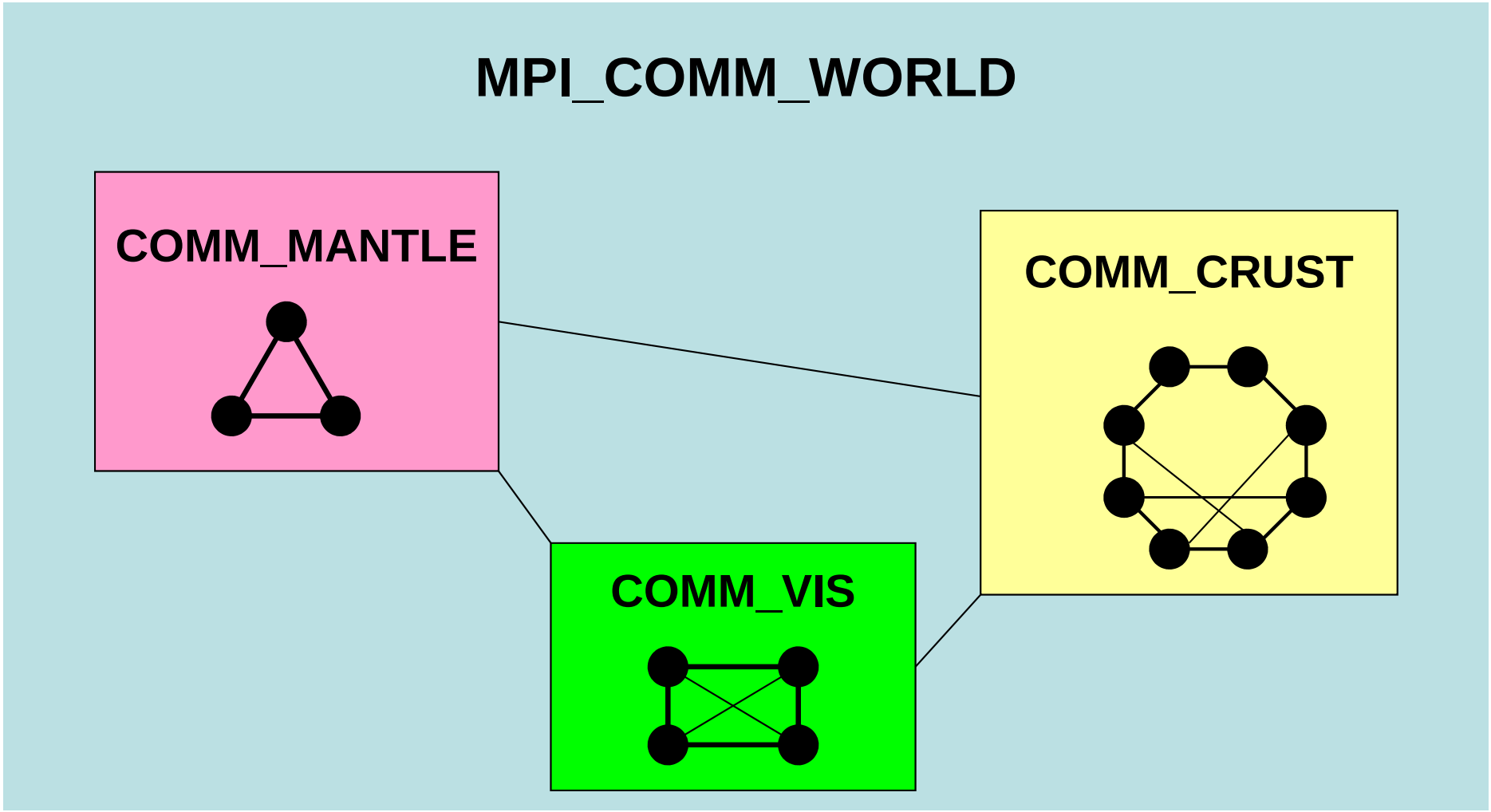
What is Communicator ?

```
MPI_Comm_Size (MPI_COMM_WORLD, PETOT)
```

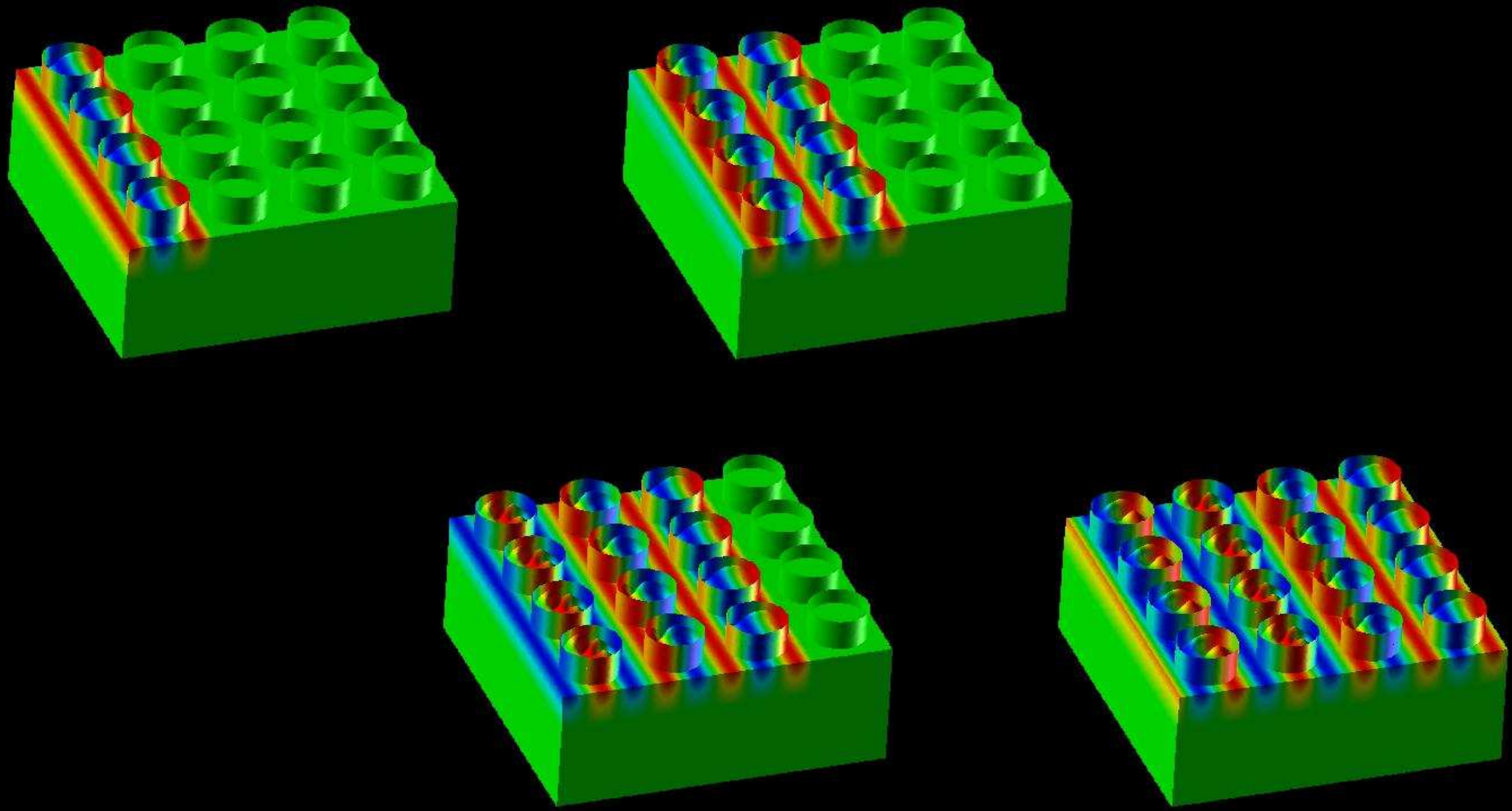
- Group of processes for communication
- Communicator must be specified in MPI program as a unit of communication
- All processes belong to a group, named "**MPI_COMM_WORLD**" (default)
- Multiple communicators can be created, and complicated operations are possible.
  - Computation, Visualization
- Only "MPI_COMM_WORLD" is needed in this class.

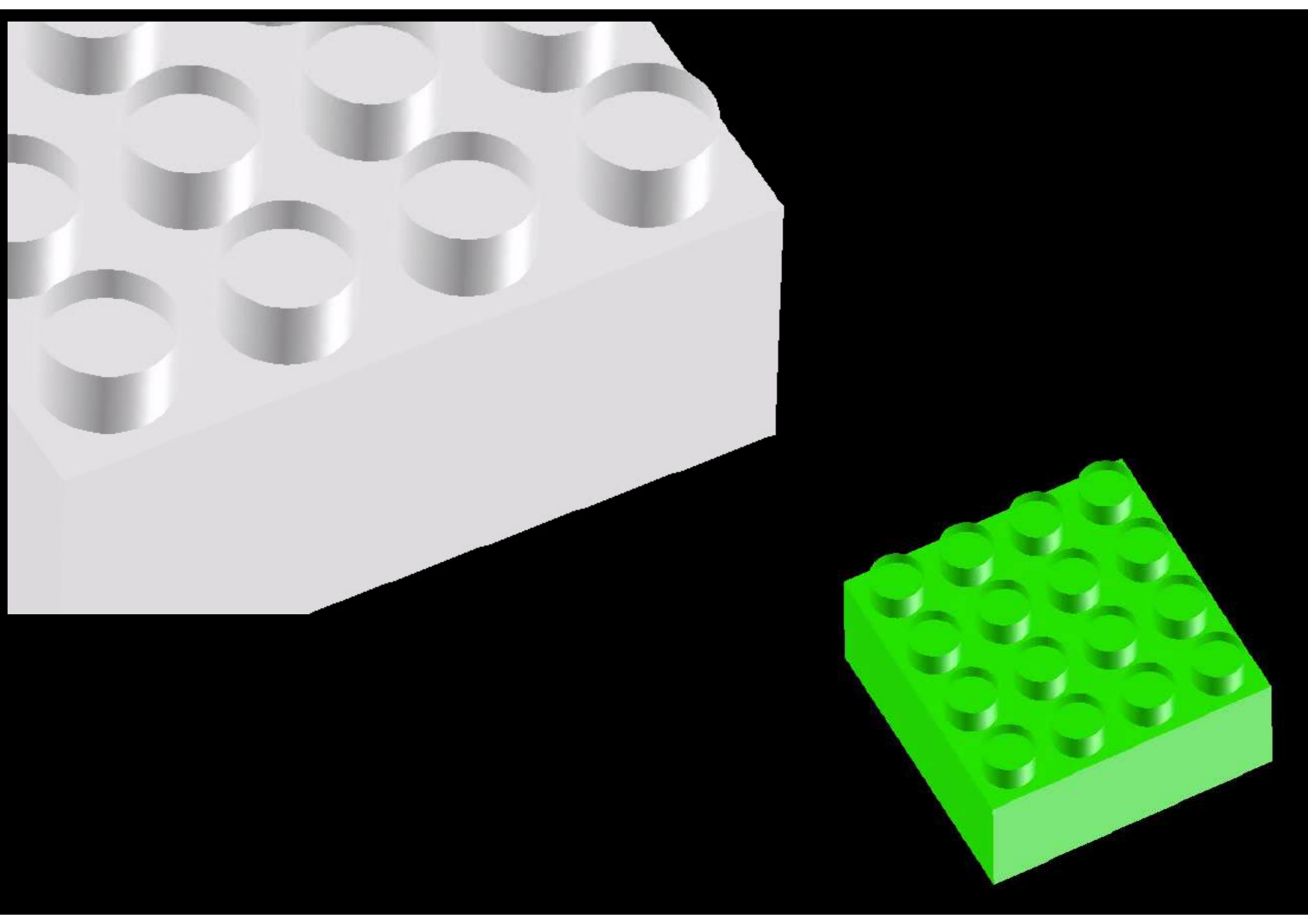
Communicator in MPI

One process can belong to multiple communicators



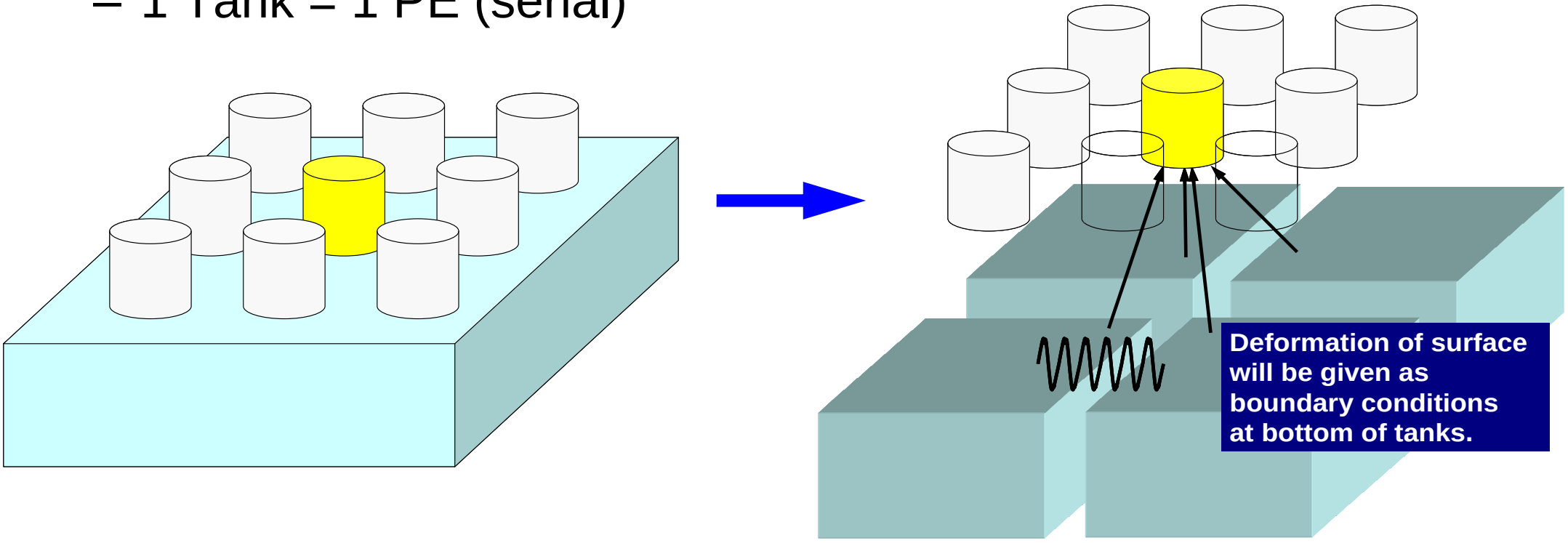
Coupling between “Ground Motion” and “Sloshing of Tanks for Oil-Storage”





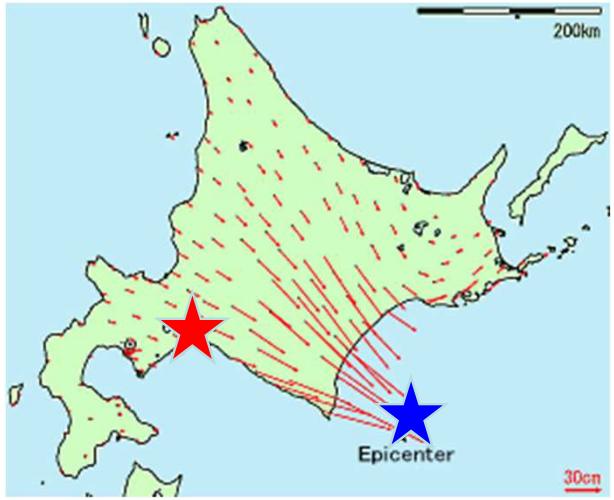
Target Application

- Coupling between “Ground Motion” and “Sloshing of Tanks for Oil-Storage”
  - “One-way” coupling from “Ground Motion” to “Tanks”.
  - Displacement of ground surface is given as forced displacement of bottom surface of tanks.
  - 1 Tank = 1 PE (serial)

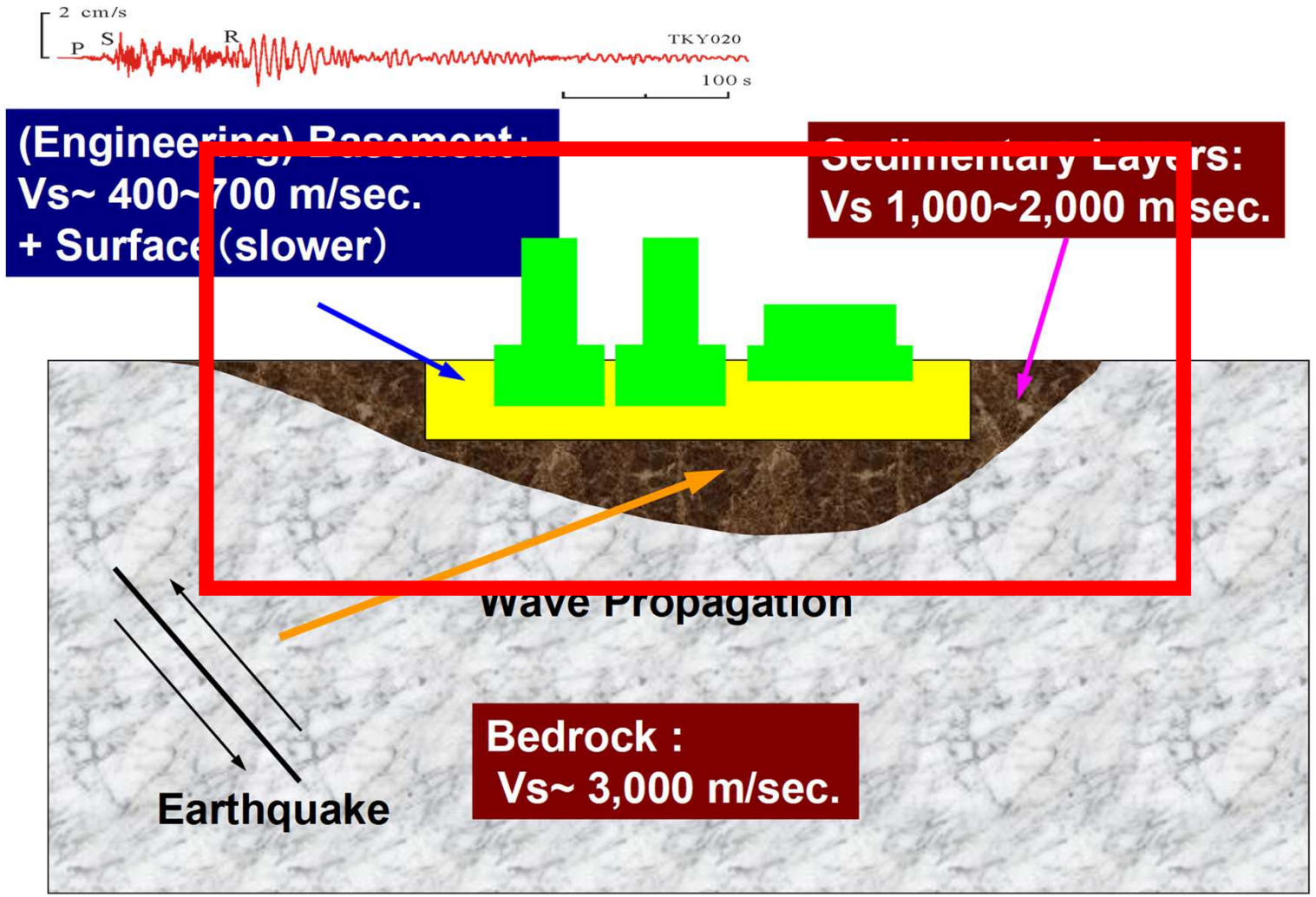


2003 Tokachi Earthquake (M8.0)

Fire accident of oil tanks due to long period
ground motion (surface waves) developed in the basin of Tomakomai

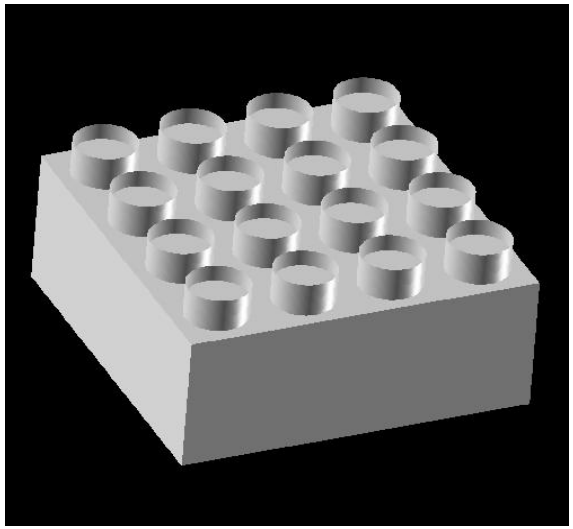


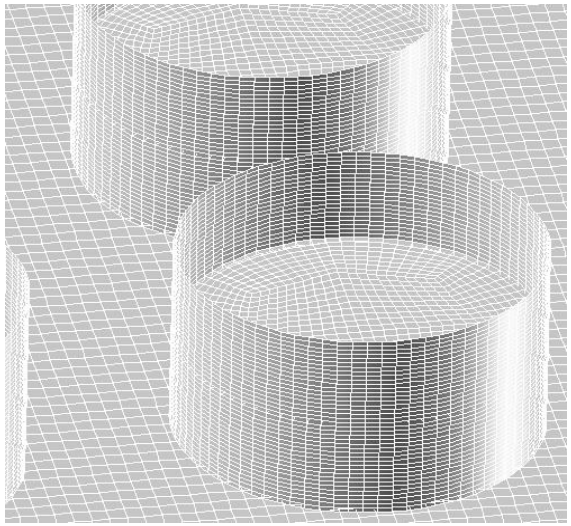
Seismic Wave Propagation, Underground Structure



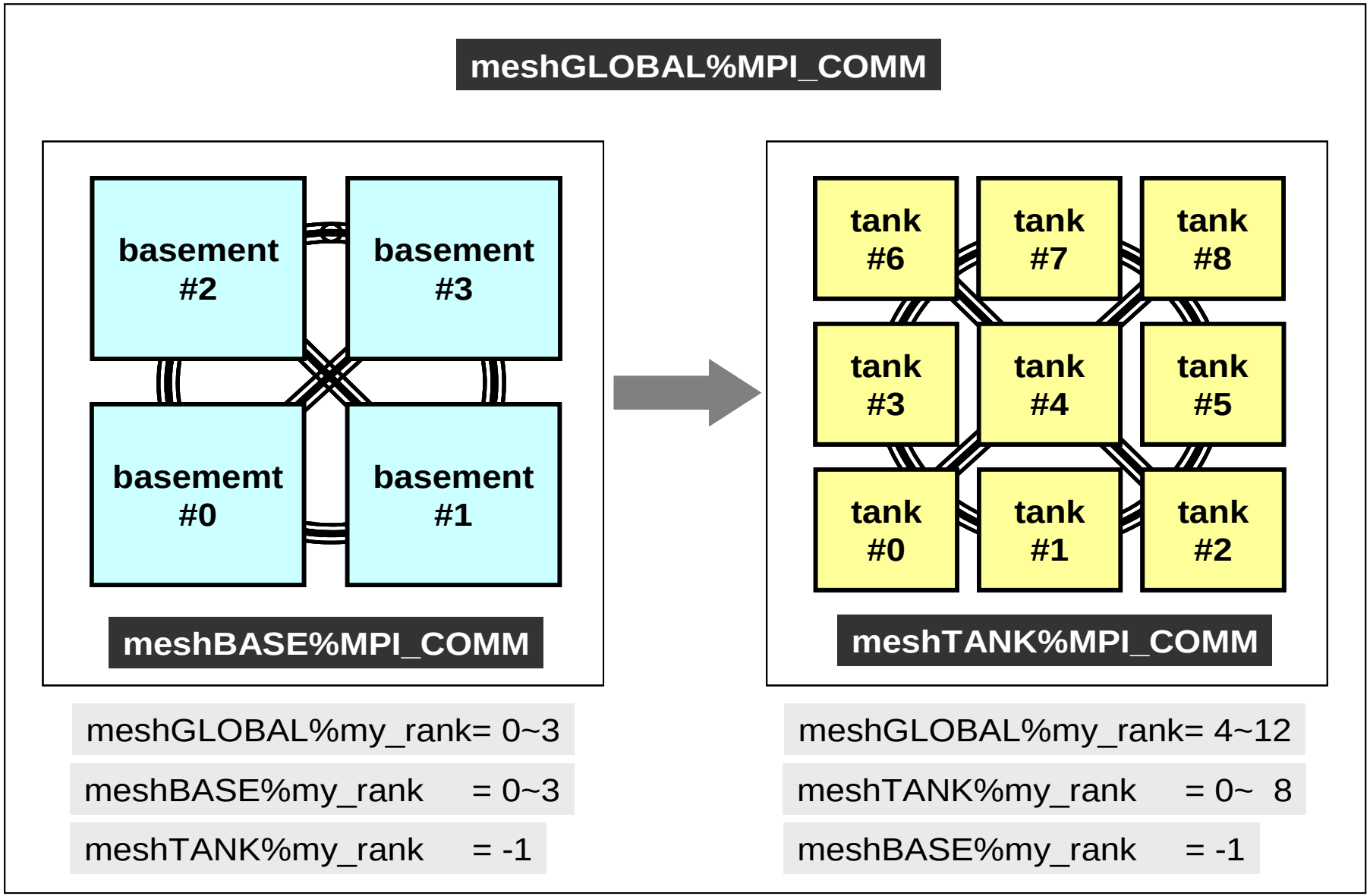
Simulation Codes

- Ground Motion (Ichimura): Fortran
  - Parallel FEM, 3D Elastic/Dynamic
    - Explicit forward Euler scheme
  - Each element: 2m × 2m × 2m cube
  - 240m × 240m × 100m region
- Sloshing of Tanks (Nagashima): C
  - Serial FEM (Embarrassingly Parallel)
    - Implicit backward Euler, Skyline method
    - Shell elements + Inviscid potential flow
  - D: 42.7m, H: 24.9m, T: 20mm,
  - Frequency: 7.6sec.
  - 80 elements in circ., 0.6m mesh in height
  - Tank-to-Tank: 60m, 4 × 4
- Total number of unknowns: 2,918,169





Three Communicators



C

MPI_Comm_rank

- Determines the rank of the calling process in the communicator
  - "ID of MPI process" is sometimes called "rank"

- **MPI_Comm_rank (comm, rank)**
  - **comm** MPI_Comm I communicator
  - **rank** int O rank of the calling process in the group of comm
    Starting from "0"

```
#include "mpi.h"
#include <stdio.h>
int main(int argc, char **argv)
{
    int n, myid, numprocs, i;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);

    printf ("Hello World %d¥n", myid);
    MPI_Finalize();
}
```

C

MPI_Abort

- Aborts MPI execution environment

- **`MPI_Abort (comm, errcode)`**
  - **`comm`** MPI_Comm I communicator
  - **`errcode`** int O error code

C

MPI_Wtime

- Returns an elapsed time on the calling processor

- **time= MPI_Wtime ()**
  - **time** double O Time in seconds since an arbitrary time in the past.

```
…
double Stime, Etime;

Stime= MPI_Wtime ();

(…)

Etime= MPI_Wtime ();
```

Example of MPI_Wtime

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1

$> mpicc -O1 time.c
$> mpiifort -O1 time.f

(modify go4.sh, 4 processes)
$> qsub go4.sh

     0    1.113281E+00
     3    1.113281E+00
     2    1.117188E+00
     1    1.117188E+00

 Process      Time
   ID
```

MPI_Wtick

- Returns the resolution of MPI_Wtime
- depends on hardware, and compiler

- **time= MPI_Wtick ()**
  - **time** double O Time in seconds of resolution of MPI_Wtime

```
implicit REAL*8 (A-H,O-Z)
include 'mpif.h'

…
TM= MPI_WTICK ()
write (*,*) TM
…
```

```
double Time;

…
Time = MPI_Wtick();
printf("%5d%16.6E¥n", MyRank, Time);
…
```

Example of MPI_Wtick

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1

$> mpicc -O1 wtick.c
$> mpiifort -O1 wtick.f

(modify go1.sh, 1 process)
$> qsub go1.sh
```

C

MPI_Barrier

- Blocks until all processes in the communicator have reached this routine.
- Mainly for debugging, huge overhead, not recommended for real code.

- **`MPI_Barrier (comm)`**
  - **`comm`** MPI_Comm I communicator

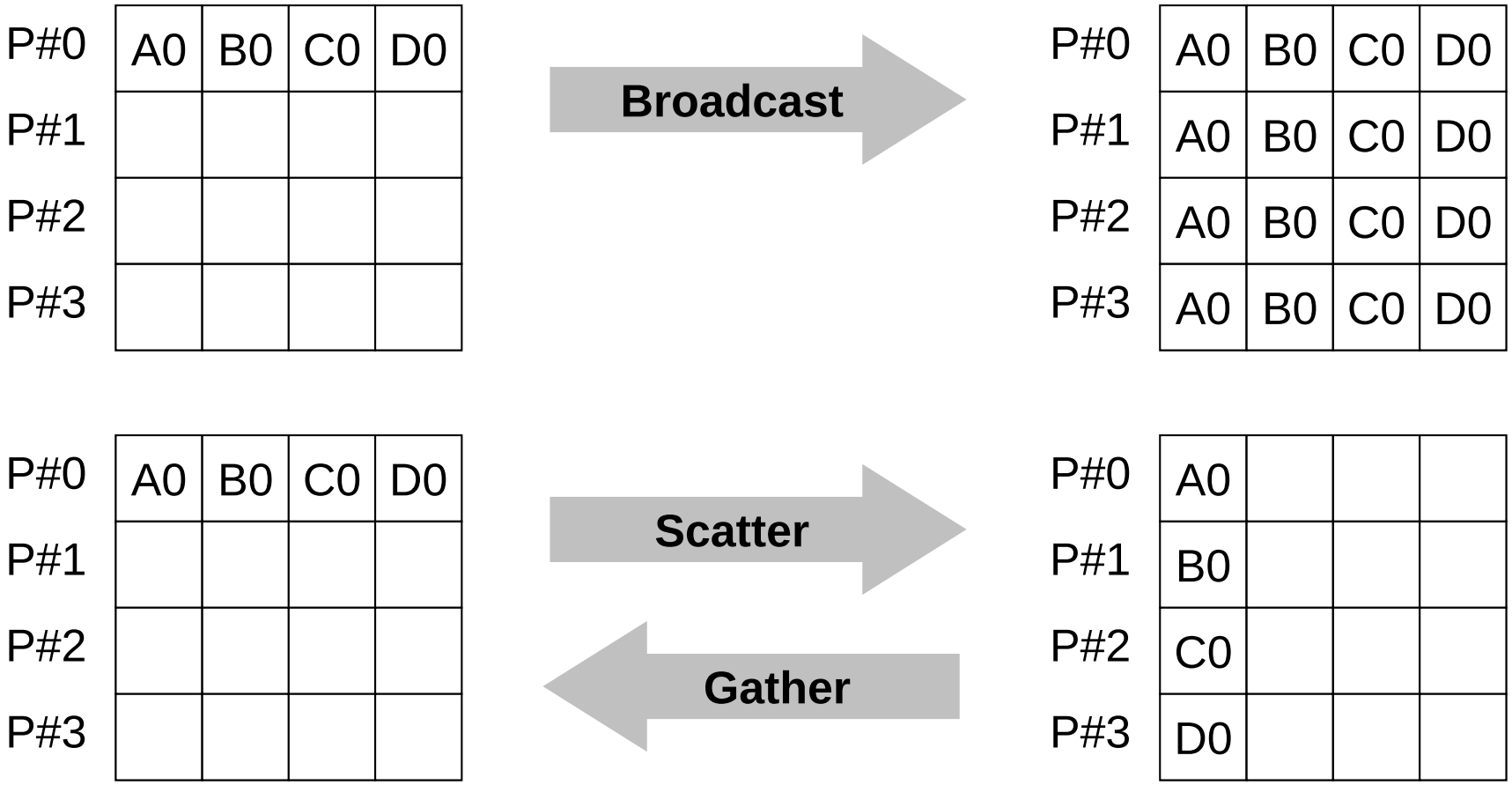
- What is MPI ?
- Your First MPI Program: Hello World
- **Collective Communication**
- Point-to-Point Communication

What is Collective Communication ?
集団通信, グループ通信

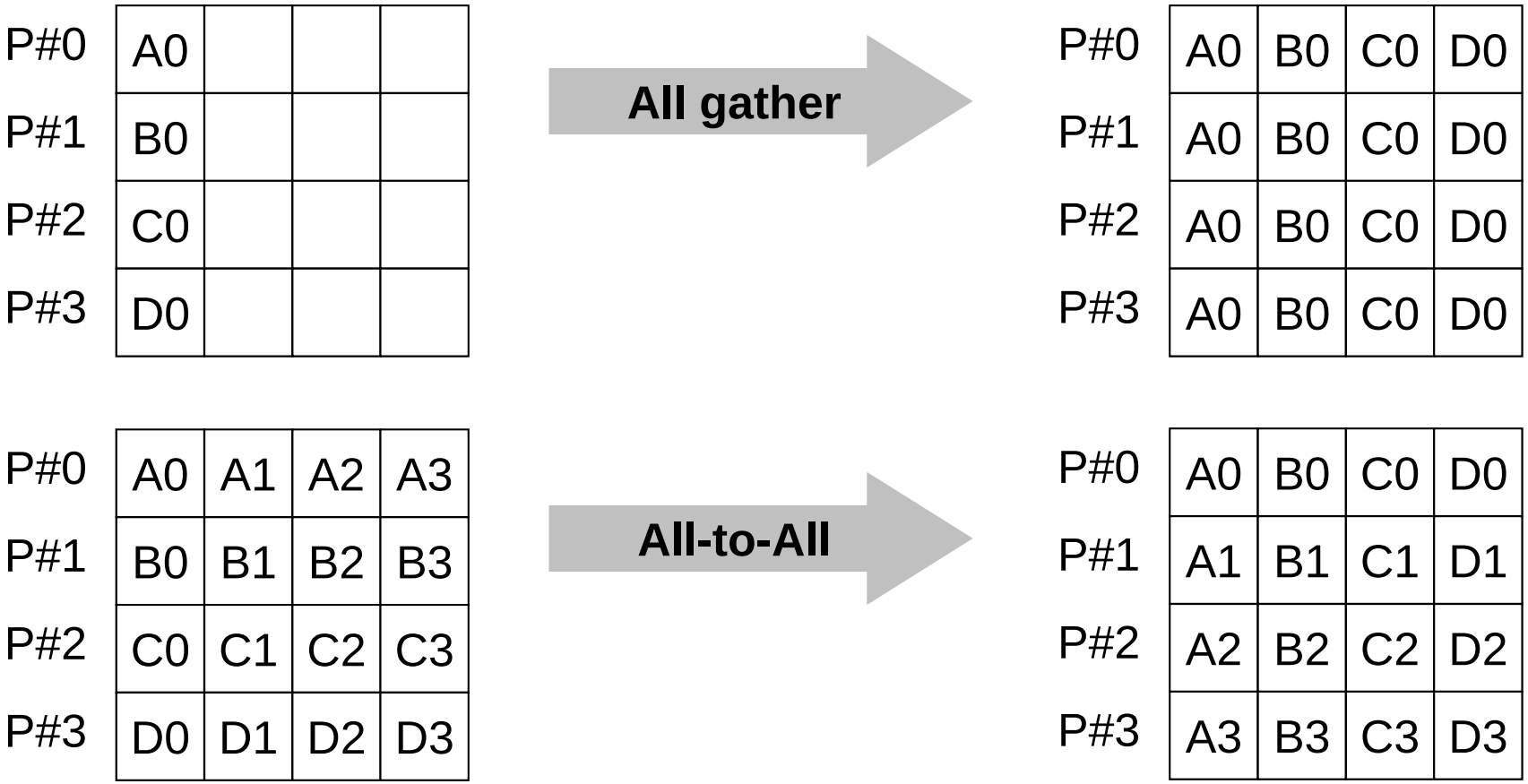
- Collective communication is the process of exchanging information between multiple MPI processes in the communicator: one-to-all or all-to-all communications.

- Examples
  - Broadcasting control data
  - Max, Min
  - Summation
  - Dot products of vectors
  - Transformation of dense matrices

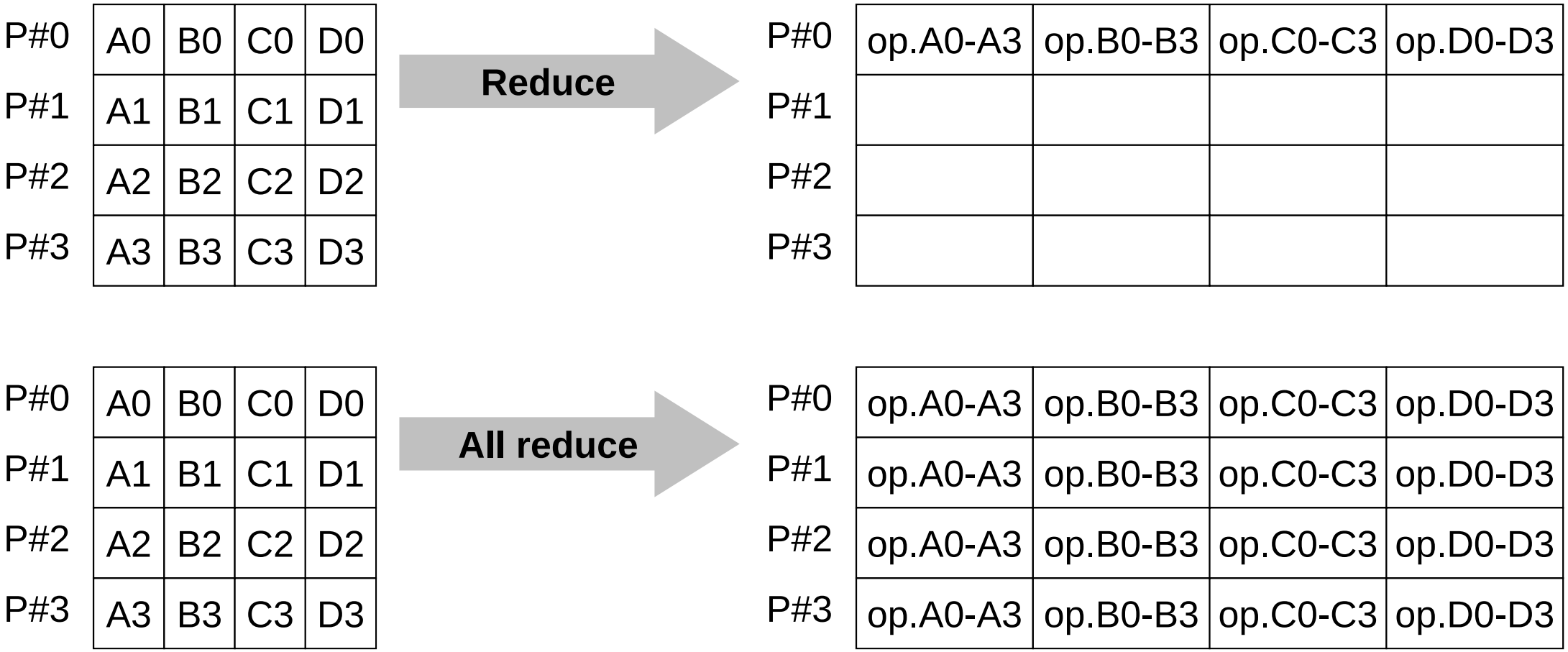
Example of Collective Communications (1/4)



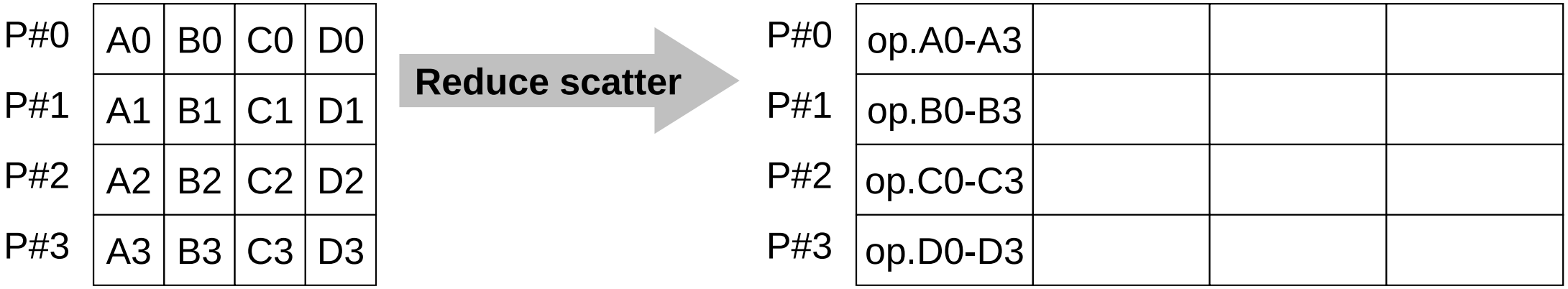
Example of Collective Communications (2/4)



Example of Collective Communications (3/4)



Example of Collective Communications (4/4)



Examples by Collective Comm.

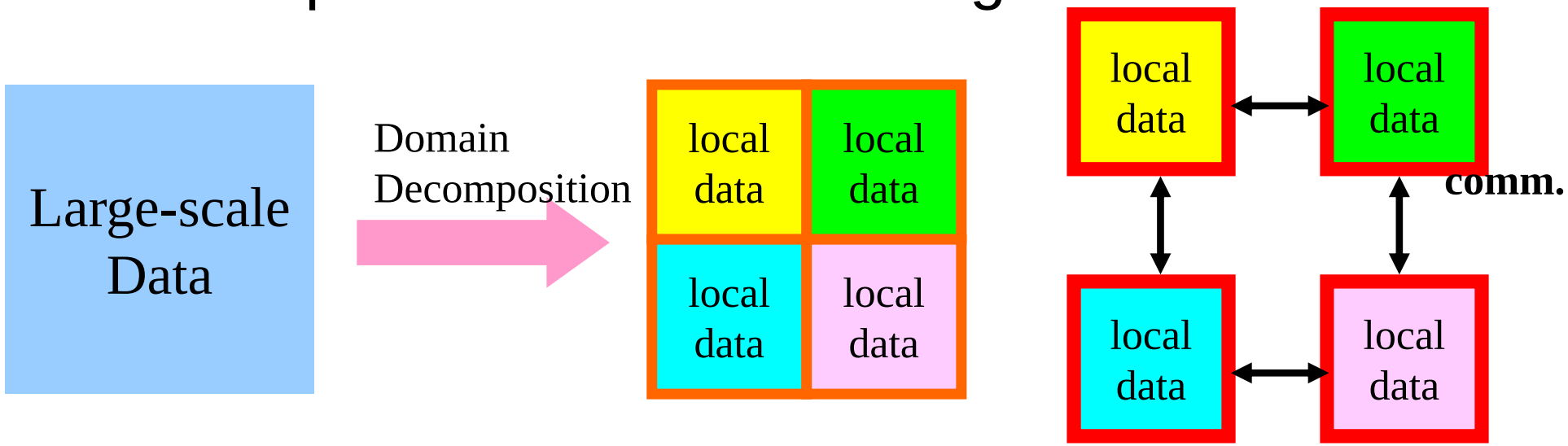
- **Dot Products of Vectors**
- Scatter/Gather
- Reading Distributed Files
- MPI_Allgatherv

Global/Local Data

- Data structure of parallel computing based on SPMD, where large scale “global data” is decomposed to small pieces of “local data”.

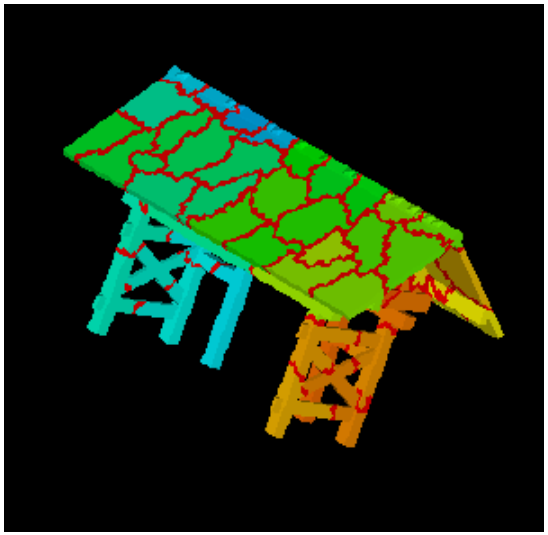
Domain Decomposition/Partitioning

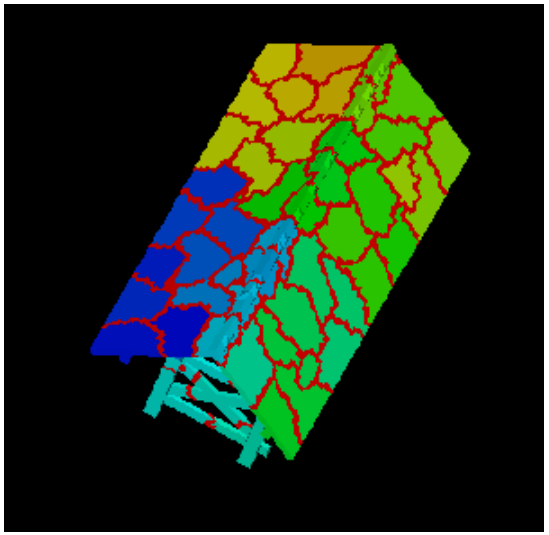
- PC with 1GB RAM: can execute FEM application with up to 10^6 meshes
  - 10^3km × 10^3 km × 10^2 km (SW Japan): 10^8 meshes by 1km cubes
- Large-scale Data: Domain decomposition, parallel & local operations
- Global Computation: Comm. among domains needed



Local Data Structure

- It is important to define proper local data structure for target computation (and its algorithm)
  - Algorithms= Data Structures
- Main objective of this class !





Global/Local Data

- Data structure of parallel computing based on SPMD, where large scale “global data” is decomposed to small pieces of “local data”.

- Consider the dot product of following VECp and VECs with length=20 by parallel computation using 4 processors

```
VECp[ 0]=  2
     [ 1]=  2
     [ 2]=  2
…
     [17]=  2
     [18]=  2
     [19]=  2
```

```
VECs[ 0]=  3
     [ 1]=  3
     [ 2]=  3
…
     [17]=  3
     [18]=  3
     [19]=  3
```

<$O-S1>/dot.f, dot.c

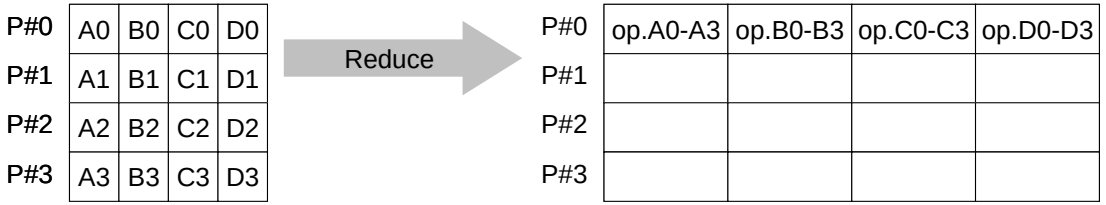
```
implicit REAL*8 (A-H,O-Z)
real(kind=8),dimension(20):: &
    VECp,  VECs

do i= 1, 20
  VECp(i)= 2.0d0
  VECs(i)= 3.0d0
enddo

sum= 0.d0
do ii= 1, 20
  sum= sum + VECp(ii)*VECs(ii)
enddo

stop
end
```

```
#include <stdio.h>
int main(){
   int i;
   double VECp[20], VECs[20]
   double sum;

   for(i=0;i<20;i++){
     VECp[i]= 2.0;
     VECs[i]= 3.0;
   }

   sum = 0.0;
   for(i=0;i<20;i++){
     sum += VECp[i] * VECs[i];
   }
   return 0;
}
```

<$O-S1>/dot.f, dot.c (do it on ECCS 2016)

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1

>$ gcc dot.c
>$ ifort dot.f

>$ ./a.out

  1          2.          3.
  2          2.          3.
  3          2.          3.
…
 18          2.          3.
 19          2.          3.
 20          2.          3.

dot product       120.
```

MPI_Reduce



- Reduces values on all processes to a single value
  - Summation, Product, Max, Min etc.

- **MPI_Reduce (sendbuf,recvbuf,count,datatype,op,root,comm)**
  - **sendbuf** choice I starting address of send buffer
  - **recvbuf** choice O starting address receive buffer
    type is defined by "**datatype**"
  - **count** int I number of elements in send/receive buffer
  - **datatype** MPI_Datatype I data type of elements of send/recive buffer
    FORTRAN MPI_INTEGER, MPI_REAL, MPI_DOUBLE_PRECISION, MPI_CHARACTER etc.
    C MPI_INT, MPI_FLOAT, MPI_DOUBLE, MPI_CHAR etc

  - **op** MPI_Op I reduce operation
    MPI_MAX, MPI_MIN, MPI_SUM, MPI_PROD, MPI_LAND, MPI_BAND etc
    Users can define operations by **MPI_OP_CREATE**

  - **root** int I rank of root process
  - **comm** MPI_Comm I communicator

C

Send/Receive Buffer (Sending/Receiving)

- Arrays of “send (sending) buffer” and “receive (receiving) buffer” often appear in MPI.

- Addresses of “send (sending) buffer” and “receive (receiving) buffer” must be different.

Send/Receive Buffer (1/3)
A: Scalar

```
call MPI_REDUCE
(A,recvbuf, 1,datatype,op,root,comm,ierr)

MPI_Reduce
(A,recvbuf,1,datatype,op,root,comm)
```

Send/Receive Buffer (2/3)
A: Array

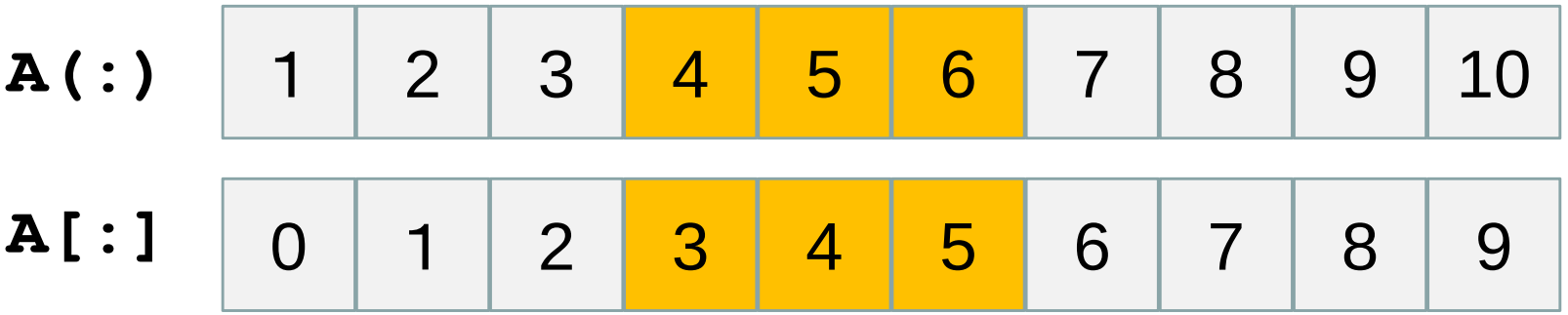
```
call MPI_REDUCE
(A,recvbuf, 3,datatype,op,root,comm,ierr)

MPI_Reduce
(A,recvbuf,3,datatype,op,root,comm)
```

- Starting Address of Send Buffer
  - `A(1)`: Fortran, `A[0]`: C
  - 3 (continuous) components of `A (A(1)-A(3), A[0]-A[2])` are sent

Send/Receive Buffer (3/3)
A: Array

```
call MPI_REDUCE
(A(4),recvbuf, 3,datatype,op,root,comm,ierr)

MPI_Reduce
(A[3],recvbuf,3,datatype,op,root,comm)
```

- Starting Address of Send Buffer
  - `A(4)`: Fortran, `A[3]`: C
  - 3 (continuous) components of `A (A(4)-A(6), A[3]-A[5])` are sent



C

Example of MPI_Reduce (1/2)

```
MPI_Reduce
(sendbuf,recvbuf,count,datatype,op,root,comm)
```

```
double X0, X1;

MPI_Reduce
(&X0, &X1, 1, MPI_DOUBLE, MPI_MAX, 0, <comm>);
```

```
double X0[4], XMAX[4];

MPI_Reduce
(X0, XMAX, 4, MPI_DOUBLE, MPI_MAX, 0, <comm>);
```

Global Max values of X0[i] go to XMAX[i] on #0 process（i=0~3）

C

Example of MPI_Reduce (2/2)

```
MPI_Reduce
(sendbuf,recvbuf,count,datatype,op,root,comm)
```

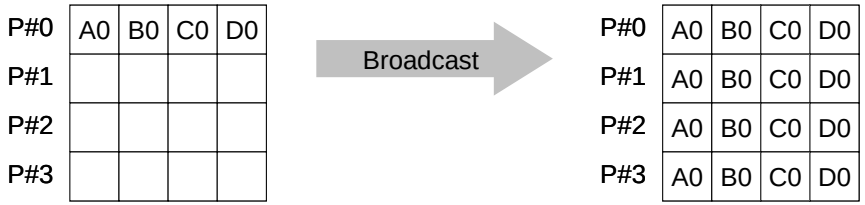
```
double X0, XSUM;

MPI_Reduce
(&X0, &XSUM, 1, MPI_DOUBLE, MPI_SUM, 0, <comm>)
```

Global summation of X0 goes to XSUM on #0 process.

```
double X0[4];

MPI_Reduce
(&X0[0], &X0[2], 2, MPI_DOUBLE_PRECISION, MPI_SUM, 0, <comm>)
```

- Global summation of X0[0] goes to X0[2] on #0 process.
- Global summation of X0[1] goes to X0[3] on #0 process.

MPI_Bcast



- Broadcasts a message from the process with rank "root" to all other processes of the communicator

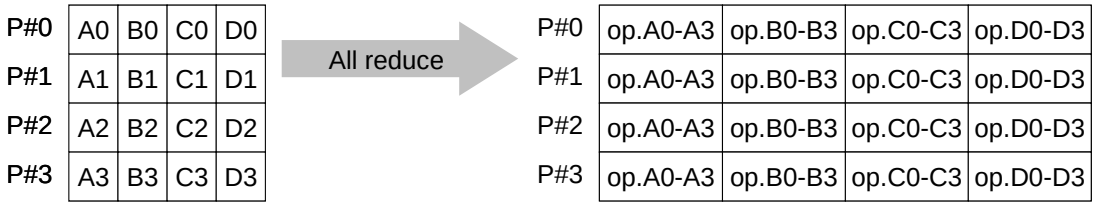
- **MPI_Bcast (buffer,count,datatype,root,comm)**
  - **buffer** choice I/O starting address of buffer
    type is defined by "**datatype**"
  - **count** int I number of elements in send/recv buffer
  - **datatype** MPI_Datatype I data type of elements of send/recv buffer

    FORTRAN MPI_INTEGER, MPI_REAL, MPI_DOUBLE_PRECISION, MPI_CHARACTER etc.

    C MPI_INT, MPI_FLOAT, MPI_DOUBLE, MPI_CHAR etc.
  - **root** int I rank of root process
  - **comm** MPI_Comm I communicator

C

MPI_Allreduce



- MPI_Reduce + MPI_Bcast
- Summation (of dot products) and MAX/MIN values are likely to utilized in each process

- **`call MPI_Allreduce`**
  `(sendbuf,recvbuf,count,datatype,op, comm)`
  - **`sendbuf`** choice I starting address of send buffer
  - **`recvbuf`** choice O starting address receive buffer
    type is defined by **"`datatype`"**
  - **`count`** int I number of elements in send/recv buffer
  - **`datatype`** MPI_Datatype I data type of elements of send/recv buffer
  - **`op`** MPI_Op I reduce operation
  - **`comm`** MPI_Comm I communicator

C

“op” of MPI_Reduce/Allreduce

C

```
MPI_Reduce
(sendbuf,recvbuf,count,datatype,op,root,comm)
```

- **MPI_MAX**, **MPI_MIN** Max, Min
- **MPI_SUM**, **MPI_PROD** Summation, Product
- **MPI_LAND** Logical AND

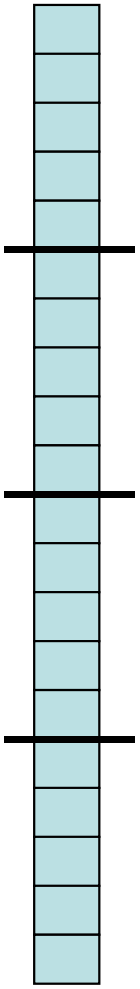
C

Local Data (1/2)

- Decompose vector with length=20 into 4 domains (processes)
- Each process handles a vector with length= 5

```
VECp[ 0]=  2
    [ 1]=  2
    [ 2]=  2
…
    [17]=  2
    [18]=  2
    [19]=  2
```

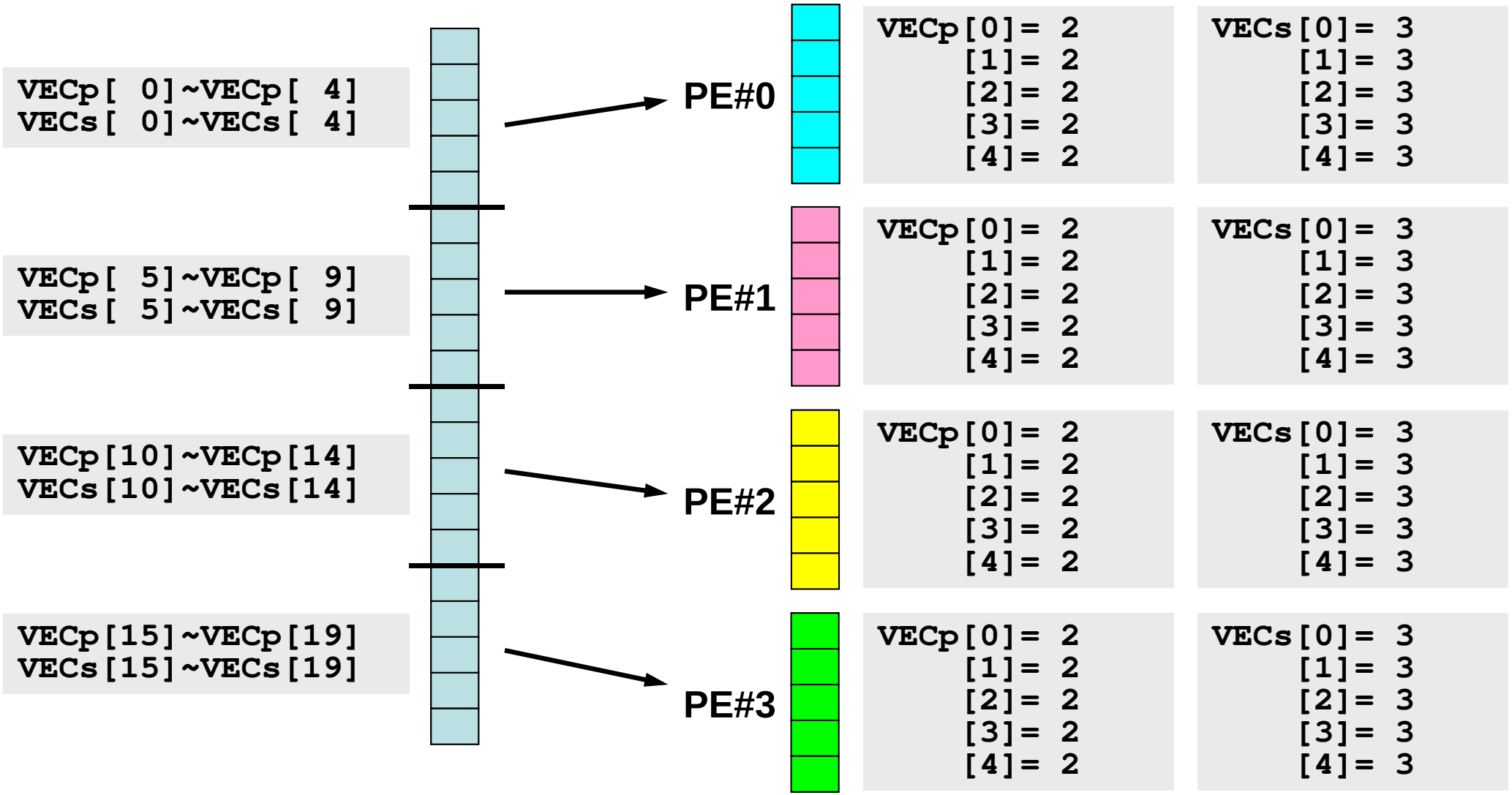
```
VECs[ 0]=  3
    [ 1]=  3
    [ 2]=  3
…
    [17]=  3
    [18]=  3
    [19]=  3
```



C

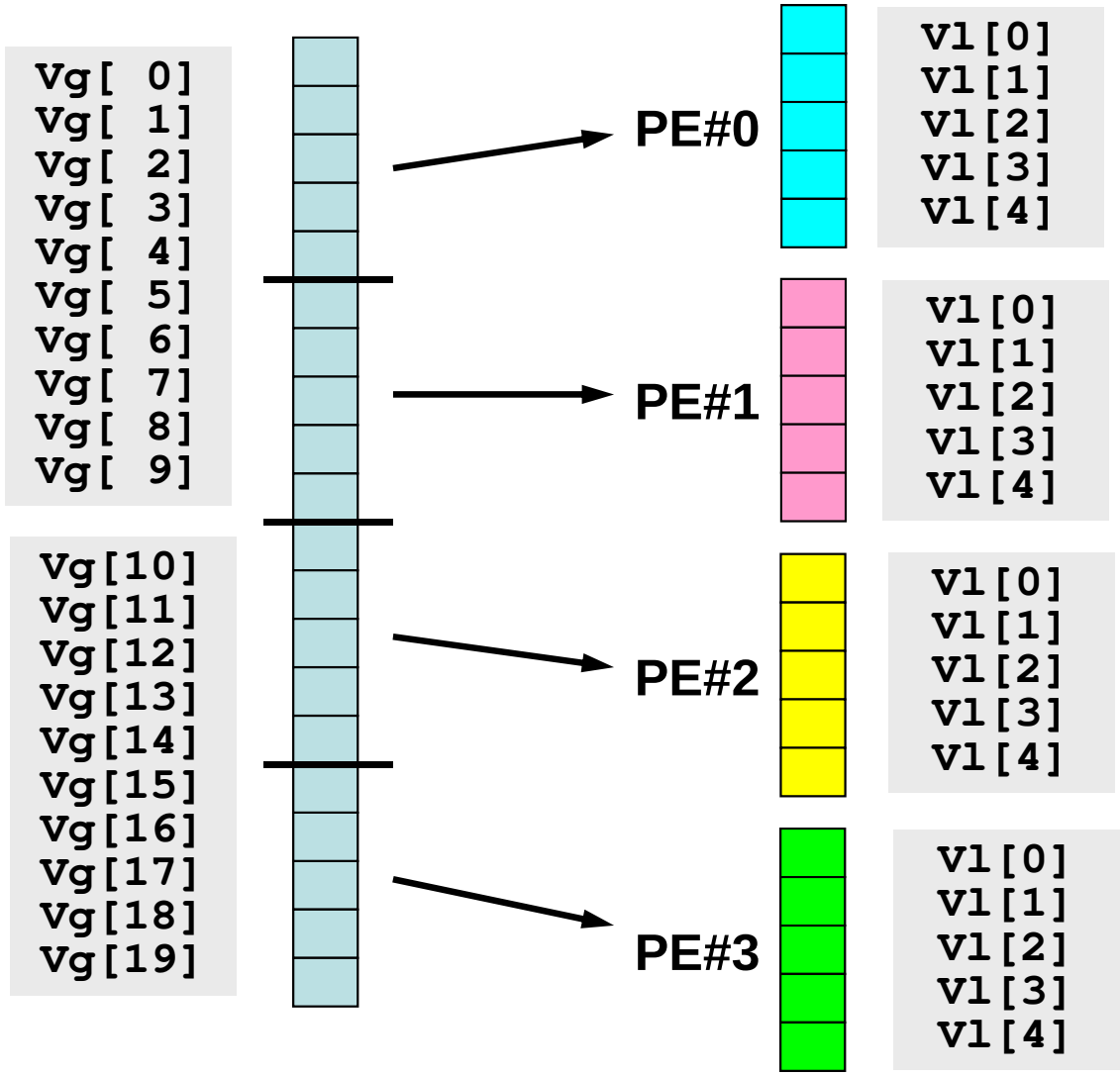
Local Data (2/2)

- 1th-5th components of original global vector go to 1th-5th components of PE#0, 6th-10th -> PE#1, 11th-15th -> PE#2, 16th-20th -> PE#3.



But ...

- It is too easy !! Just decomposing and renumbering from 1 (or 0).
- Of course, this is not enough. Further examples will be shown in the latter part.



Example: Dot Product (1/3)

<$O-S1>/allreduce.c

```
#include <stdio.h>
#include <stdlib.h>
#include "mpi.h"

int main(int argc, char **argv){
        int i,N;
        int PeTot, MyRank;
        double VECp[5], VECs[5];
        double sumA, sumR, sum0;

        MPI_Init(&argc, &argv);
        MPI_Comm_size(MPI_COMM_WORLD, &PeTot);
        MPI_Comm_rank(MPI_COMM_WORLD, &MyRank);

        sumA= 0.0;
        sumR= 0.0;

        N=5;
        for(i=0;i<N;i++){
          VECp[i] = 2.0;
          VECs[i] = 3.0;
        }

        sum0 = 0.0;
        for(i=0;i<N;i++){
                sum0 += VECp[i] * VECs[i];
        }
```

Local vector is generated at each local process.

Example: Dot Product (2/3)

<$O-S1>/allreduce.c

```
        MPI_Reduce(&sum0, &sumR, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);
        MPI_Allreduce(&sum0, &sumA, 1, MPI_DOUBLE, MPI_SUM, MPI_COMM_WORLD);
        printf("before BCAST %5d %15.0F %15.0F¥n", MyRank, sumA, sumR);

        MPI_Bcast(&sumR, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
        printf("after  BCAST %5d %15.0F %15.0F¥n", MyRank, sumA, sumR);

        MPI_Finalize();

        return 0;
}
```

Example: Dot Product (3/3)

<$O-S1>/allreduce.c

```
MPI_Reduce(&sum0, &sumR, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);

MPI_Allreduce(&sum0, &sumA, 1, MPI_DOUBLE, MPI_SUM, MPI_COMM_WORLD);
```

Dot Product
Summation of results of each process (sum0)
"sumR" has value only on PE#0.

"sumA" has value on all processes by MPI_Allreduce

```
MPI_Bcast(&sumR, 1, MPI_DOUBLE, 0, MPI_COMM_WORLD);
```

"sumR" has value on PE#1-#3 by MPI_Bcast

Execute <$O-S1>/allreduce.f/c

```
$> cd /lustre/gt18/t18XXX/pFEM/mpi/S1
$> mpiifort -O3 allreduce.f
(modify go4.sh, 4 process)
$> qsub go4.sh

(my_rank, sumALLREDUCE,sumREDUCE)
before BCAST    0    1.200000E+02    1.200000E+02
after  BCAST    0    1.200000E+02    1.200000E+02

before BCAST    1    1.200000E+02    0.000000E+00
after  BCAST    1    1.200000E+02    1.200000E+02

before BCAST    3    1.200000E+02    0.000000E+00
after  BCAST    3    1.200000E+02    1.200000E+02

before BCAST    2    1.200000E+02    0.000000E+00
after  BCAST    2    1.200000E+02    1.200000E+02
```

Examples by Collective Comm.

- Dot Products of Vectors
- **Scatter/Gather**
- Reading Distributed Files
- MPI_Allgatherv

Global/Local Data (1/3)

- Parallelization of an easy process where a real number α is added to each component of real vector **VECg**:

```
      do i= 1, NG
        VECg(i)= VECg(i) + ALPHA
      enddo
```

```
for (i=0; i<NG; i++{
    VECg[i]= VECg[i] + ALPHA
}
```

Global/Local Data (2/3)

- Configurationa
  - **NG= 32 (length of the vector)**
  - **ALPHA=1000.**
  - Process # of MPI= 4

- Vector VECg has following 32 components (<$T-S1>/a1x.all):

```
(101.0,  103.0,  105.0,  106.0,  109.0,  111.0,  121.0,  151.0,
 201.0,  203.0,  205.0,  206.0,  209.0,  211.0,  221.0,  251.0,
 301.0,  303.0,  305.0,  306.0,  309.0,  311.0,  321.0,  351.0,
 401.0,  403.0,  405.0,  406.0,  409.0,  411.0,  421.0,  451.0)
```

Global/Local Data (3/3)

- Procedure
  - ① Reading vector **VECg** with length=32 from one process (*e.g.* 0th process)
    - Global Data
  - ② Distributing vector components to 4 MPI processes equally (*i.e.* length= 8 for each processes)
    - Local Data, Local ID/Numbering
  - ③ Adding **ALPHA** to each component of the local vector (with length= 8) on each process.
  - ④ Merging the results to global vector with length= 32.

- Actually, we do not need parallel computers for such a kind of small computation.

Operations of Scatter/Gather (1/8)

Reading **VECg** (length=32) from a process (*e.g.* #0)

- Reading global data from #0 process

```
include   'mpif.h'
integer,  parameter :: NG= 32
real(kind=8), dimension(NG):: VECg

call MPI_INIT (ierr)
call MPI_COMM_SIZE (<comm>, PETOT  , ierr)
call MPI_COMM_RANK (<comm>, my_rank, ierr)

if (my_rank.eq.0) then
  open (21, file= 'a1x.all', status= 'unknown')
  do i= 1, NG
    read (21,*) VECg(i)
  enddo
  close (21)
endif
```

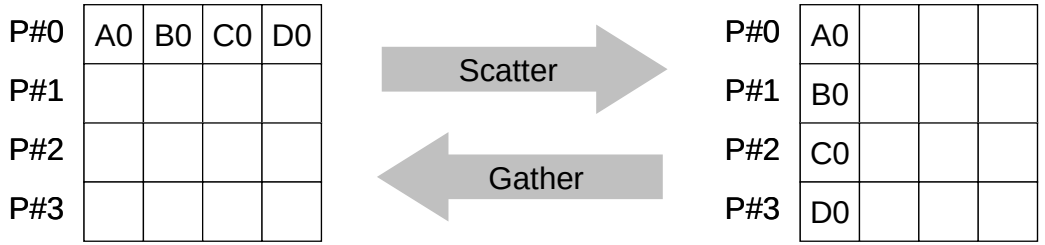
```
#include <mpi.h>
#include <stdio.h>
#include <math.h>
#include <assert.h>

int main(int argc, char **argv){
  int i, NG=32;
  int PeTot, MyRank, MPI_Comm;
  double VECg[32];
  char filename[80];
  FILE *fp;

  MPI_Init(&argc, &argv);
  MPI_Comm_size(<comm>, &PeTot);
  MPI_Comm_rank(<comm>, &MyRank);

        fp = fopen("a1x.all", "r");
        if(!MyRank) for(i=0;i<NG;i++){
                fscanf(fp, "%lf", &VECg[i]);
        }
```

Operations of Scatter/Gather (2/8)

Distributing global data to 4 process equally (*i.e.* length=8 for each process)

- MPI_Scatter

MPI_Scatter



- Sends data from one process to all other processes in a communicator
  - `scount`-size messages are sent to each process

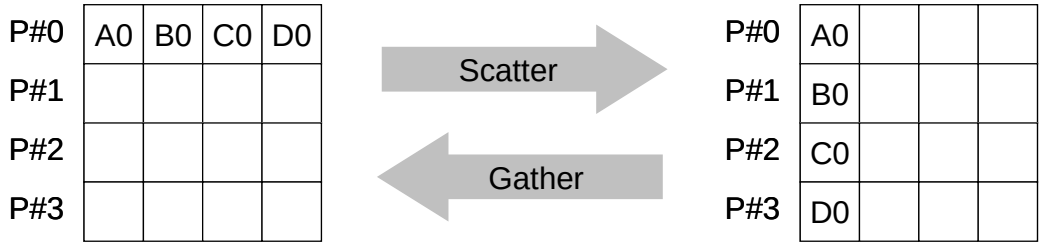
- **`MPI_Scatter (sendbuf, scount, sendtype, recvbuf, rcount, recvtype, root, comm)`**
  - **`sendbuf`** choice I — starting address of sending buffer
    type is defined by "**`datatype`**"
  - **`scount`** int I — number of elements sent to each process
  - **`sendtype`** MPI_Datatype I — data type of elements of sending buffer

    FORTRAN `MPI_INTEGER, MPI_REAL, MPI_DOUBLE_PRECISION, MPI_CHARACTER etc.`

    C `MPI_INT, MPI_FLOAT, MPI_DOUBLE, MPI_CHAR etc.`
  - **`recvbuf`** choice O — starting address of receiving buffer
  - **`rcount`** int I — number of elements received from the root process
  - **`recvtype`** MPI_Datatype I — data type of elements of receiving buffer
  - **`root`** int I — rank of root process
  - **`comm`** MPI_Comm I — communicator

C

MPI_Scatter (cont.)



- **MPI_Scatter (sendbuf, scount, sendtype, recvbuf, rcount, recvtype, root, comm)**
  - **sendbuf** choice I starting address of sending buffer
  - **scount** int I number of elements sent to each process
  - **sendtype** MPI_Datatype I data type of elements of sending buffer
  - **recvbuf** choice O starting address of receiving buffer
  - **rcount** int I number of elements received from the root process
  - **recvtype** MPI_Datatype I data type of elements of receiving buffer
  - **root** int I rank of root process
  - **comm** MPI_Comm I communicator

- Usually
  - **scount = rcount**
  - **sendtype= recvtype**
- This function sends **scount** components starting from **sendbuf** (sending buffer) at process **#root** to each process in **comm**. Each process receives **rcount** components starting from **recvbuf** (receiving buffer).

C

Operations of Scatter/Gather (3/8)

Distributing global data to 4 processes equally

- Allocating receiving buffer **VEC** (length=8) at each process.
- 8 components sent from sending buffer **VECg** of process #0 are received at each process #0-#3 as 1st-8th components of receiving buffer **VEC**.

```
integer, parameter :: N =  8
real(kind=8), dimension(N ) :: VEC
...
call MPI_Scatter                              &
     (VECg, N, MPI_DOUBLE_PRECISION, &
      VEC , N, MPI_DOUBLE_PRECISION, &
      0, <comm>, ierr)
```

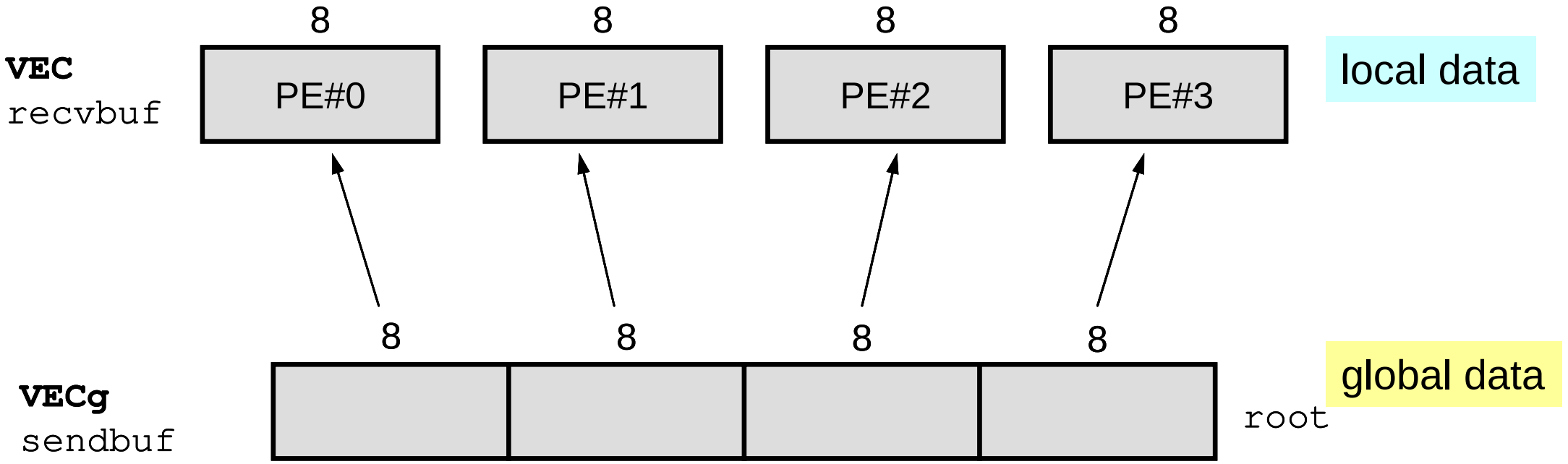
```
int  N=8;
double VEC [8];
...
MPI_Scatter  (VECg,  N,  MPI_DOUBLE,  VEC,  N,
MPI_DOUBLE, 0, <comm>);
```

```
call MPI_SCATTER
(sendbuf, scount, sendtype, recvbuf, rcount,
 recvtype, root, comm, ierr)
```

Operations of Scatter/Gather (4/8)

Distributing global data to 4 processes equally

- 8 components are *scattered* to each process from root (#0)
- 1st-8th components of **VECg** are stored as 1st-8th ones of **VEC** at **#0**, 9th-16th components of **VECg** are stored as 1st-8th ones of **VEC** at **#1**, etc.
  - **VECg**: Global Data, **VEC**: Local Data



Operations of Scatter/Gather (5/8)

Distributing global data to 4 processes equally

- Global Data: 1st-32nd components of **VECg** at **#0**
- Local Data: 1st-8th components of **VEC** at each process
- Each component of **VEC** can be written from each process in the following way:

```
do i= 1, N
  write (*,'(a, 2i8,f10.0)') 'before',  my_rank, i, VEC(i)
enddo
```

```
for(i=0;i<N;i++){
printf("before %5d %5d %10.0F¥n", MyRank, i+1, VEC[i]);}
```

Operations of Scatter/Gather (5/8)

Distributing global data to 4 processes equally

- Global Data: 1st-32nd components of **VECg** at **#0**
- Local Data: 1st-8th components of **VEC** at each process
- Each component of **VEC** can be written from each process in the following way:

```
PE#0
before 0 1   101.
before 0 2   103.
before 0 3   105.
before 0 4   106.
before 0 5   109.
before 0 6   111.
before 0 7   121.
before 0 8   151.
```

```
PE#1
before 1 1   201.
before 1 2   203.
before 1 3   205.
before 1 4   206.
before 1 5   209.
before 1 6   211.
before 1 7   221.
before 1 8   251.
```

```
PE#2
before 2 1   301.
before 2 2   303.
before 2 3   305.
before 2 4   306.
before 2 5   309.
before 2 6   311.
before 2 7   321.
before 2 8   351.
```

```
PE#3
before 3 1   401.
before 3 2   403.
before 3 3   405.
before 3 4   406.
before 3 5   409.
before 3 6   411.
before 3 7   421.
before 3 8   451.
```

Operations of Scatter/Gather (6/8)

On each process, **ALPHA** is added to each of 8 components of **VEC**

- On each process, computation is in the following way

```
real(kind=8), parameter :: ALPHA= 1000.
do i= 1, N
  VEC(i)= VEC(i) + ALPHA
enddo
```

```
double ALPHA=1000.;
...
for(i=0;i<N;i++){
  VEC[i]= VEC[i] + ALPHA;}
```

- Results:

PE#0
```
after 0 1  1101.
after 0 2  1103.
after 0 3  1105.
after 0 4  1106.
after 0 5  1109.
after 0 6  1111.
after 0 7  1121.
after 0 8  1151.
```

PE#1
```
after 1 1  1201.
after 1 2  1203.
after 1 3  1205.
after 1 4  1206.
after 1 5  1209.
after 1 6  1211.
after 1 7  1221.
after 1 8  1251.
```

PE#2
```
after 2 1  1301.
after 2 2  1303.
after 2 3  1305.
after 2 4  1306.
after 2 5  1309.
after 2 6  1311.
after 2 7  1321.
after 2 8  1351.
```

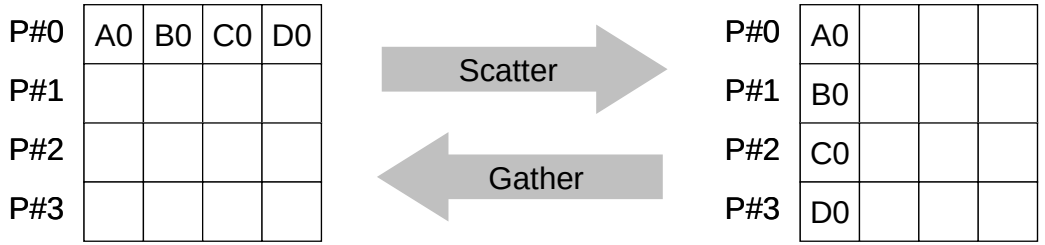
PE#3
```
after 3 1  1401.
after 3 2  1403.
after 3 3  1405.
after 3 4  1406.
after 3 5  1409.
after 3 6  1411.
after 3 7  1421.
after 3 8  1451.
```

Operations of Scatter/Gather (7/8)

Merging the results to global vector with length= 32

- Using MPI_Gather (inverse operation to MPI_Scatter)

MPI_Gather



- Gathers together values from a group of processes, inverse operation to MPI_Scatter

- **`MPI_Gather (sendbuf, scount, sendtype, recvbuf, rcount, recvtype, root, comm)`**
  - **`sendbuf`** choice I — starting address of sending buffer
  - **`scount`** int I — number of elements sent to each process
  - **`sendtype`** MPI_Datatype I — data type of elements of sending buffer
  - **`recvbuf`** choice O — starting address of receiving buffer
  - **`rcount`** int I — number of elements received from the root process
  - **`recvtype`** MPI_Datatype I — data type of elements of receiving buffer
  - **`root`** int I — rank of root process
  - **`comm`** MPI_Comm I — communicator

- **`recvbuf`** is on **`root`** process.

C

Operations of Scatter/Gather (8/8)

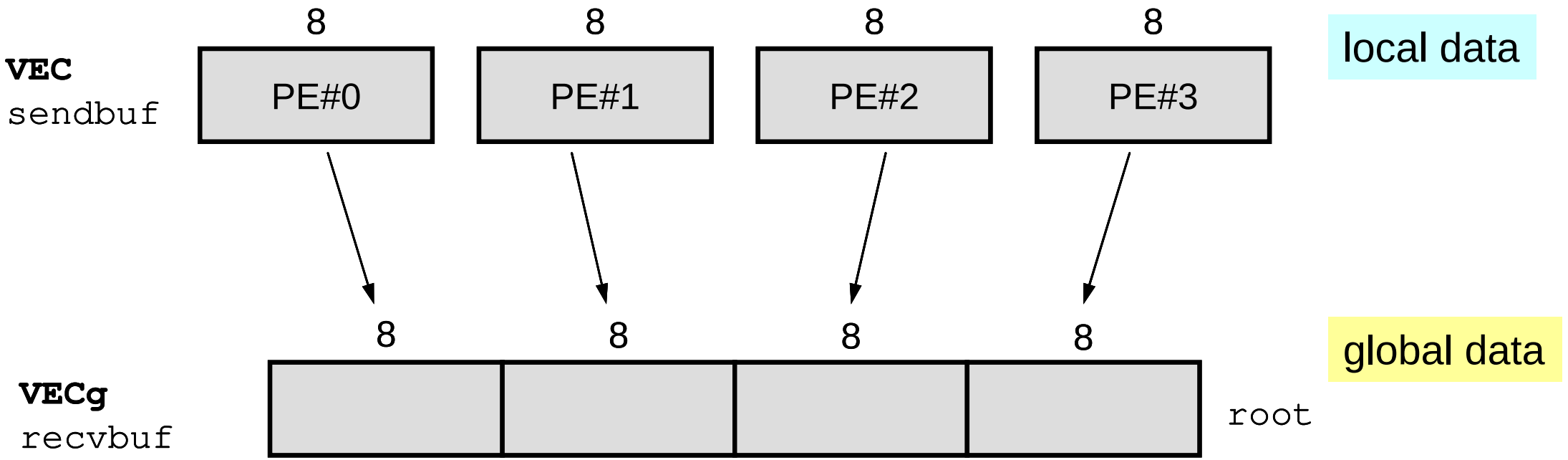
Merging the results to global vector with length= 32

- Each process components of **VEC** to **VECg** on root (#0 in this case).

```
call MPI_Gather                                    &
     (VEC , N, MPI_DOUBLE_PRECISION, &
      VECg, N, MPI_DOUBLE_PRECISION, &
      0, <comm>, ierr)
```

```
MPI_Gather (VEC, N, MPI_DOUBLE, VECg, N,
MPI_DOUBLE, 0, <comm>);
```

- 8 components are gathered from each process to the root process.



<$O-S1>/scatter-gather.f/c example

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1
$> mpicc -O3 scatter-gather.c
$> mpiifort -O3 scatter-gather.f
$> (exec.4 proc's) qsub go4.sh
```

PE#0
```
before 0 1   101.
before 0 2   103.
before 0 3   105.
before 0 4   106.
before 0 5   109.
before 0 6   111.
before 0 7   121.
before 0 8   151.
```

PE#1
```
before 1 1   201.
before 1 2   203.
before 1 3   205.
before 1 4   206.
before 1 5   209.
before 1 6   211.
before 1 7   221.
before 1 8   251.
```

PE#2
```
before 2 1   301.
before 2 2   303.
before 2 3   305.
before 2 4   306.
before 2 5   309.
before 2 6   311.
before 2 7   321.
before 2 8   351.
```

PE#3
```
before 3 1   401.
before 3 2   403.
before 3 3   405.
before 3 4   406.
before 3 5   409.
before 3 6   411.
before 3 7   421.
before 3 8   451.
```

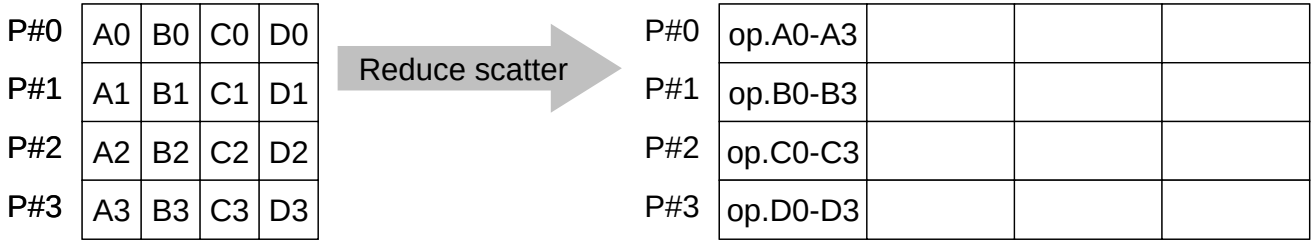
PE#0
```
after 0 1   1101.
after 0 2   1103.
after 0 3   1105.
after 0 4   1106.
after 0 5   1109.
after 0 6   1111.
after 0 7   1121.
after 0 8   1151.
```

PE#1
```
after 1 1   1201.
after 1 2   1203.
after 1 3   1205.
after 1 4   1206.
after 1 5   1209.
after 1 6   1211.
after 1 7   1221.
after 1 8   1251.
```

PE#2
```
after 2 1   1301.
after 2 2   1303.
after 2 3   1305.
after 2 4   1306.
after 2 5   1309.
after 2 6   1311.
after 2 7   1321.
after 2 8   1351.
```

PE#3
```
after 3 1   1401.
after 3 2   1403.
after 3 3   1405.
after 3 4   1406.
after 3 5   1409.
after 3 6   1411.
after 3 7   1421.
after 3 8   1451.
```

MPI_Reduce_scatter

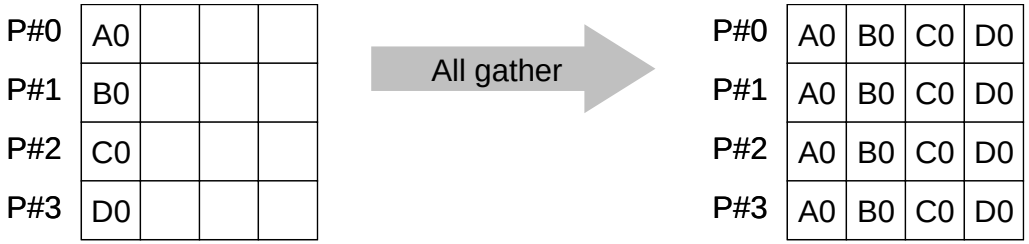


- MPI_Reduce + MPI_Scatter

- **MPI_Reduce_Scatter (sendbuf, recvbuf, rcount, datatype, op, comm)**
  - **sendbuf** choice I starting address of sending buffer
  - **recvbuf** choice O starting address of receiving buffer
  - **rcount** int I integer array specifying the number of elements in result distributed to each process. Array must be identical on all calling processes.
  - **datatype** MPI_Datatype I data type of elements of sending/receiving buffer
  - **op** MPI_Op I reduce operation
    MPI_MAX, MPI_MIN, MPI_SUM, MPI_PROD, MPI_LAND, MPI_BAND etc
  - **comm** MPI_Comm I communicator

C

MPI_Allgather

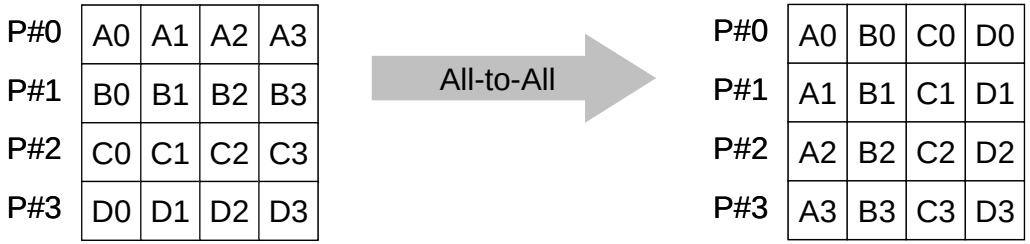


- MPI_Gather＋MPI_Bcast
  - Gathers data from all tasks and distribute the combined data to all tasks

- **MPI_Allgather (sendbuf, scount, sendtype, recvbuf, rcount, recvtype, comm)**
  - **sendbuf** choice I starting address of sending buffer
  - **scount** int I number of elements sent to each process
  - **sendtype** MPI_Datatype I data type of elements of sending buffer
  - **recvbuf** choice O starting address of receiving buffer
  - **rcount** int I number of elements received from each process
  - **recvtype** MPI_Datatype I data type of elements of receiving buffer
  - **comm** MPI_Comm I communicator

C

MPI_Alltoall



- Sends data from all to all processes: transformation of dense matrix

- **MPI_Alltoall (sendbuf, scount, sendtype, recvbuf, rcount, recvtype, comm)**
  - **sendbuf** choice I — starting address of sending buffer
  - **scount** int I — number of elements sent to each process
  - **sendtype** MPI_Datatype I — data type of elements of sending buffer
  - **recvbuf** choice O — starting address of receiving buffer
  - **rcount** int I — number of elements received from the root process
  - **recvtype** MPI_Datatype I — data type of elements of receiving buffer
  - **comm** MPI_Comm I — communicator

C

Examples by Collective Comm.

- Dot Products of Vectors
- Scatter/Gather
- **Reading Distributed Files**
- MPI_Allgatherv

Operations of Distributed Local Files

- In Scatter/Gather example, PE#0 reads global data, that is *scattered* to each processer, then parallel operations are done.

- If the problem size is very large, a single processor may not read entire global data.
  - If the entire global data is decomposed to distributed local data sets, each process can read the local data.
  - If global operations are needed to a certain sets of vectors, MPI functions, such as MPI_Gather etc. are available.

Reading Distributed Local Files: Uniform Vec. Length (1/2)

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1
>$ ls a1.*
    a1.0 a1.1 a1.2 a1.3
>$ mpicc -O3 file.c
>$ mpiifort -O3 file.f
(modify go4.sh for 4 processes)
>$ qsub go4.sh
```

a1x.all is decomposed to 4 files.

a1.0
101.0
103.0
105.0
106.0
109.0
111.0
121.0
151.0

a1.1
201.0
203.0
205.0
206.0
209.0
211.0
221.0
251.0

a1.2
301.0
303.0
305.0
306.0
309.0
311.0
321.0
351.0

a1.3
401.0
403.0
405.0
406.0
409.0
411.0
421.0
451.0

go4.sh

```
#!/bin/sh
#PBS -q u-lecture8                          Name of "QUEUE"
#PBS -N test                                Job Name
#PBS -l select=1:mpiprocs=4                 node#, proc#/node
#PBS -Wgroup_list=gt18                      Group Name (Wallet)
#PBS -l walltime=00:05:00                   Computation Time
#PBS -e err                                 Standard Error
#PBS -o test.lst                            Standard Outpt

cd $PBS_O_WORKDIR                           go to current dir
. /etc/profile.d/modules.sh                 (ESSENTIAL)

export I_MPI_PIN_DOMAIN=socket              Execution on each socket
export I_MPI_PERHOST=4                      =mpiprocs, stable
mpirun ./impimap.sh ./a.out                 Exec's
```

Reading Distributed Local Files: Uniform Vec. Length (2/2)

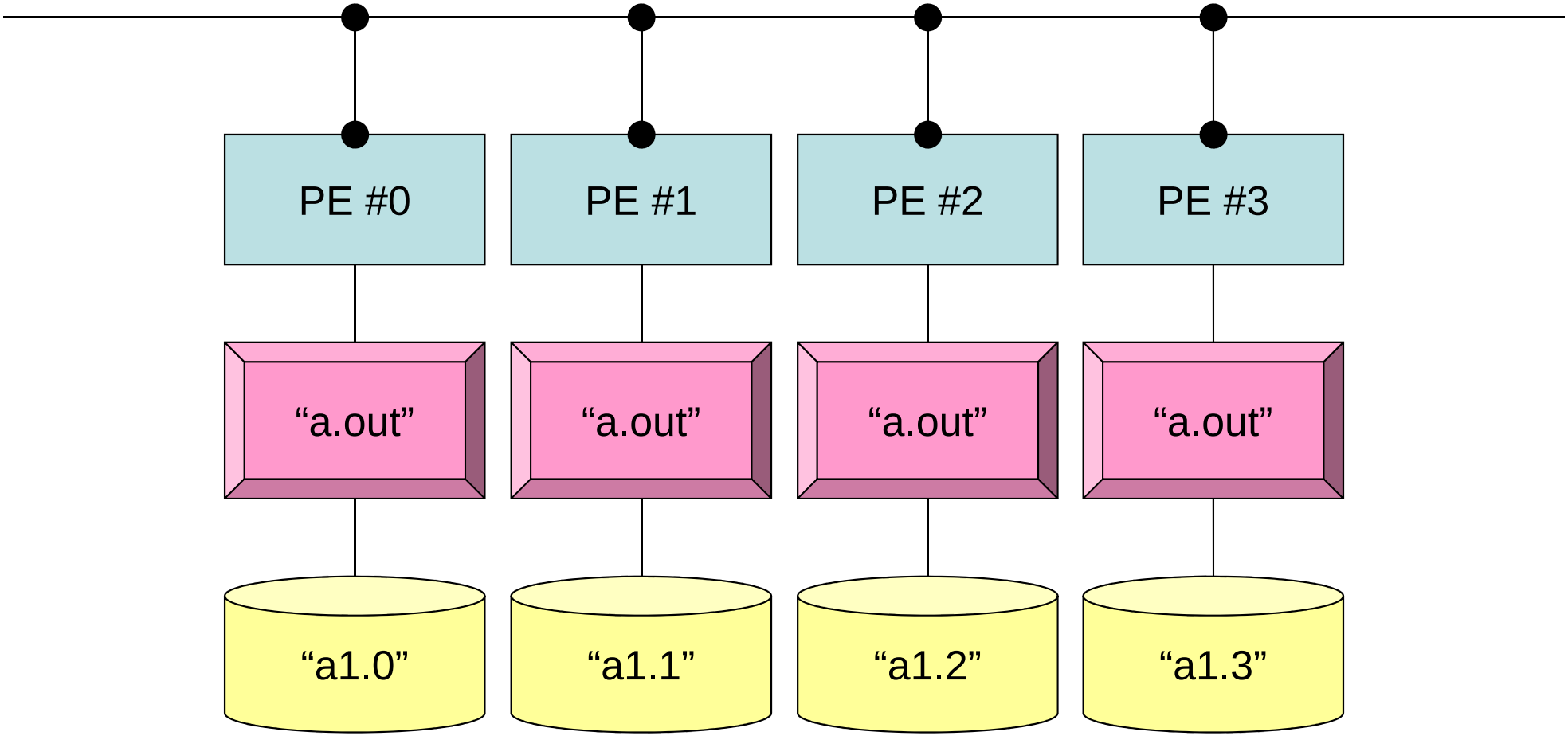
<$O-S1>/file.c

```
int main(int argc, char **argv){
        int i;
        int PeTot, MyRank;
        MPI_Comm SolverComm;
        double vec[8];
        char FileName[80];
        FILE *fp;

        MPI_Init(&argc, &argv);
        MPI_Comm_size(MPI_COMM_WORLD, &PeTot);
        MPI_Comm_rank(MPI_COMM_WORLD, &MyRank);

        sprintf(FileName, "a1.%d", MyRank);

        fp = fopen(FileName, "r");
        if(fp == NULL) MPI_Abort(MPI_COMM_WORLD, -1)
        for(i=0;i<8;i++){
                fscanf(fp, "%lf", &vec[i]);         }

        for(i=0;i<8;i++){
                printf("%5d%5d%10.0f¥n", MyRank, i+1, vec[i]);
        }
        MPI_Finalize();
        return 0;
}
```

Similar to "Hello"

Local ID is 0-7

Typical SPMD Operation




```
mpirun –np 4 a.out
```

Non-Uniform Vector Length (1/2)

```
>$ cd /lustre/gt18/t18XXX/pFEM/mpi/S1
>$ ls a2.*
   a2.0 a2.1 a2.2 a2.3
>$ cat a2.0
  5          Number of Components at each Process
  201.0      Components
  203.0
  205.0
  206.0
  209.0

>$ mpicc -O3 file2.c
>$ mpiifort -O3 file2.f

(modify go4.sh for 4 processes)
>$ qsub go4.sh
```

a2.0~a2.3

PE#0

```
   8
101.0
103.0
105.0
106.0
109.0
111.0
121.0
151.0
```

PE#1

```
   5
201.0
203.0
205.0
206.0
209.0
```

PE#2

```
   7
301.0
303.0
305.0
306.0
311.0
321.0
351.0
```

PE#3

```
   3
401.0
403.0
405.0
```

Non-Uniform Vector Length (2/2)

<$O-S1>/file2.c

```
int main(int argc, char **argv){
        int i, int PeTot, MyRank;
        MPI_Comm SolverComm;
        double *vec, *vec2, *vecg;
        int num;
        double sum0, sum;
        char filename[80];
        FILE *fp;

        MPI_Init(&argc, &argv);
        MPI_Comm_size(MPI_COMM_WORLD, &PeTot);
        MPI_Comm_rank(MPI_COMM_WORLD, &MyRank);

        sprintf(filename, "a2.%d", MyRank);
        fp = fopen(filename, "r");
        assert(fp != NULL);

        fscanf(fp, "%d", &num);
        vec = malloc(num * sizeof(double));
        for(i=0;i<num;i++){fscanf(fp, "%lf", &vec[i]);}

        for(i=0;i<num;i++){
                printf(" %5d%5d%5d%10.0f¥n", MyRank, i+1, num, vec[i]);}

        MPI_Finalize();
}
```

"num" is different at each process

How to generate local data

- Reading global data (N=NG)
  - Scattering to each process
  - Parallel processing on each process
  - (If needed) reconstruction of global data by gathering local data
- Generating local data (N=NL), or reading distributed local data
  - Generating or reading local data on each process
  - Parallel processing on each process
  - (If needed) reconstruction of global data by gathering local data

- In future, latter case is more important, but former case is also introduced in this class for understanding of operations of global/local data.

Examples by Collective Comm.

- Dot Products of Vectors
- Scatter/Gather
- Reading Distributed Files
- **MPI_Allgatherv**

MPI_Gatherv, MPI_Scatterv

- MPI_Gather, MPI_Scatter
  - Length of message from/to each process is uniform

- MPI_XXXv extends functionality of MPI_XXX by allowing a varying count of data from each process:
  - MPI_Gatherv
  - MPI_Scatterv
  - MPI_Allgatherv
  - MPI_Alltoallv

C

MPI_Allgatherv

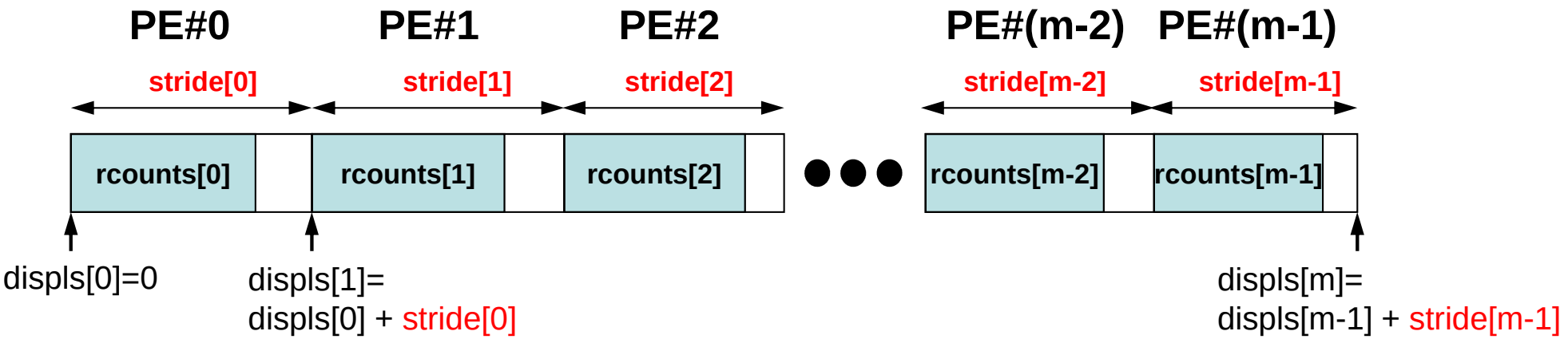
- Variable count version of MPI_Allgather
  - creates “global data” from “local data”

- **MPI_Allgatherv (sendbuf, scount, sendtype, recvbuf, rcounts, displs, recvtype, comm)**
  - **sendbuf** choice I starting address of sending buffer
  - **scount** int I number of elements sent to each process
  - **sendtype** MPI_Datatype I data type of elements of sending buffer
  - **recvbuf** choice O starting address of receiving buffer
  - **rcounts** int I integer array (of length *groupsize*) containing the number of elements that are to be received from each process (array: size= PETOT)
  - **displs** int I integer array (of length *groupsize*). Entry *i* specifies the displacement (relative to recvbuf) at which to place the incoming data from process *i* (array: size= PETOT+1)
  - **recvtype** MPI_Datatype I data type of elements of receiving buffer
  - **comm** MPI_Comm I communicator

C

MPI_Allgatherv (cont.)

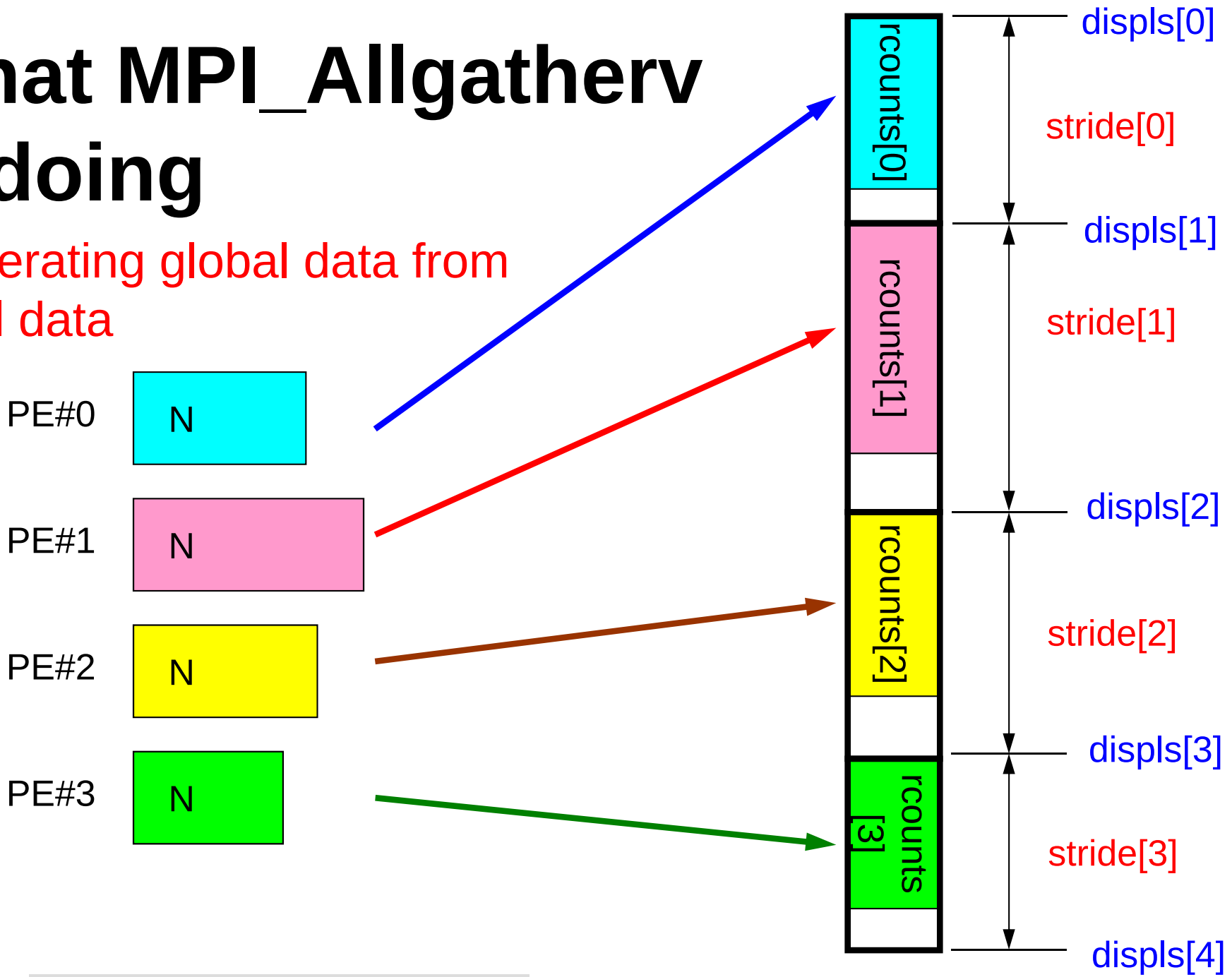
- **`MPI_Allgatherv (sendbuf, scount, sendtype, recvbuf, rcounts, displs, recvtype, comm)`**
  - **`rcounts`** int I integer array (of length *groupsize*) containing the number of elements that are to be received from each process (array: size= `PETOT`)
  - **`displs`** int I integer array (of length *groupsize*). Entry *`i`* specifies the displacement (relative to recvbuf) at which to place the incoming data from process *`i`* (array: size= `PETOT+1`)
  - These two arrays are related to size of final “global data”, therefore each process requires information of these arrays (`rcounts, displs`)
    - Each process must have same values for all components of both vectors
  - Usually, **`stride(i)=rcounts(i)`**



size[recvbuf]= displs[PETOT]= sum[stride]

What MPI_Allgatherv is doing

Generating global data from local data

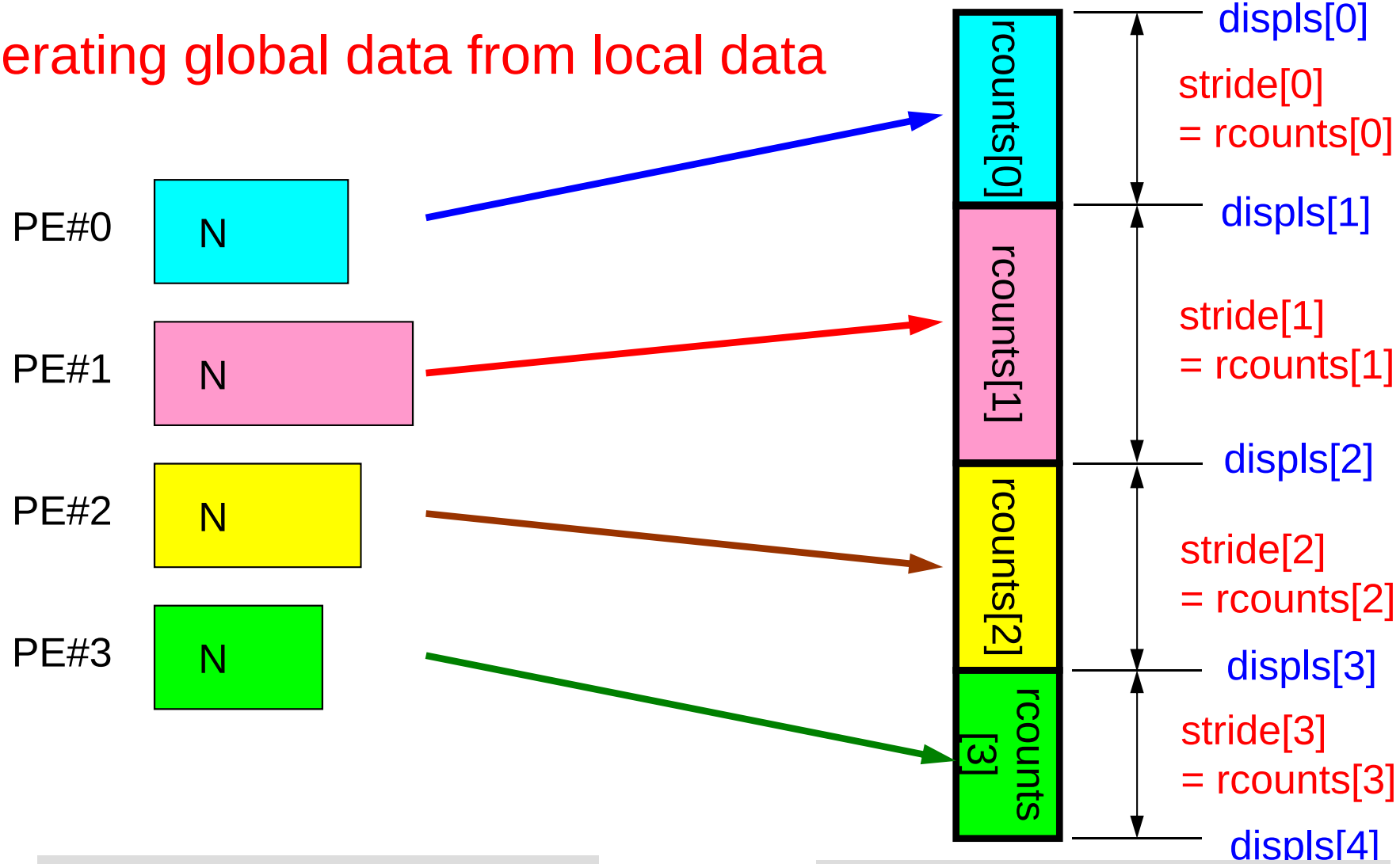


Local Data: sendbuf

Global Data: recvbuf

What MPI_Allgatherv is doing

Generating global data from local data



Local Data: sendbuf

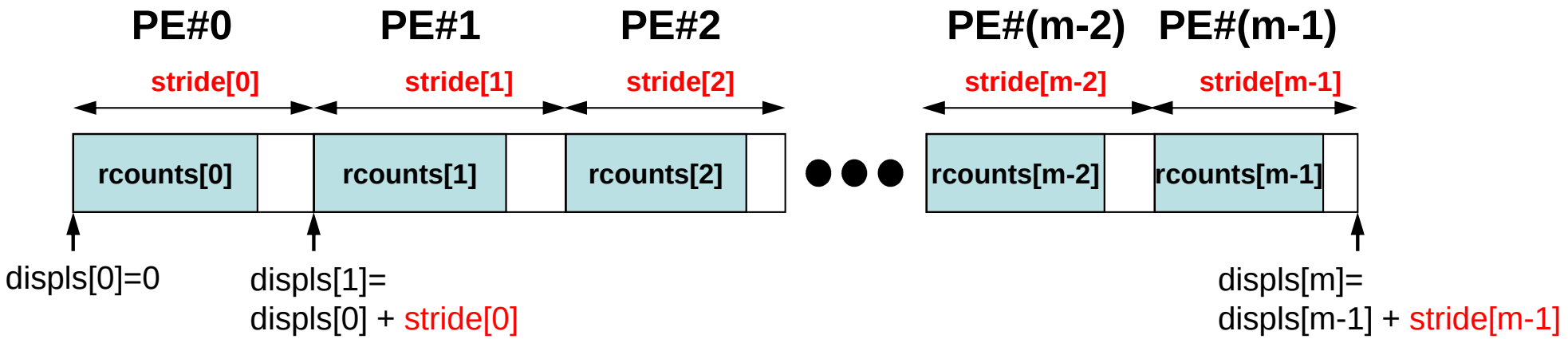
Global Data: recvbuf

MPI_Allgatherv in detail (1/2)

C

- **`MPI_Allgatherv (sendbuf, scount, sendtype, recvbuf, rcounts, displs, recvtype, comm)`**

- **`rcounts`**
  - Size of message from each PE: Size of Local Data (Length of Local Vector)
- **`displs`**
  - Address/index of each local data in the vector of global data
  - **`displs(PETOT+1)`** = Size of Entire Global Data (Global Vector)

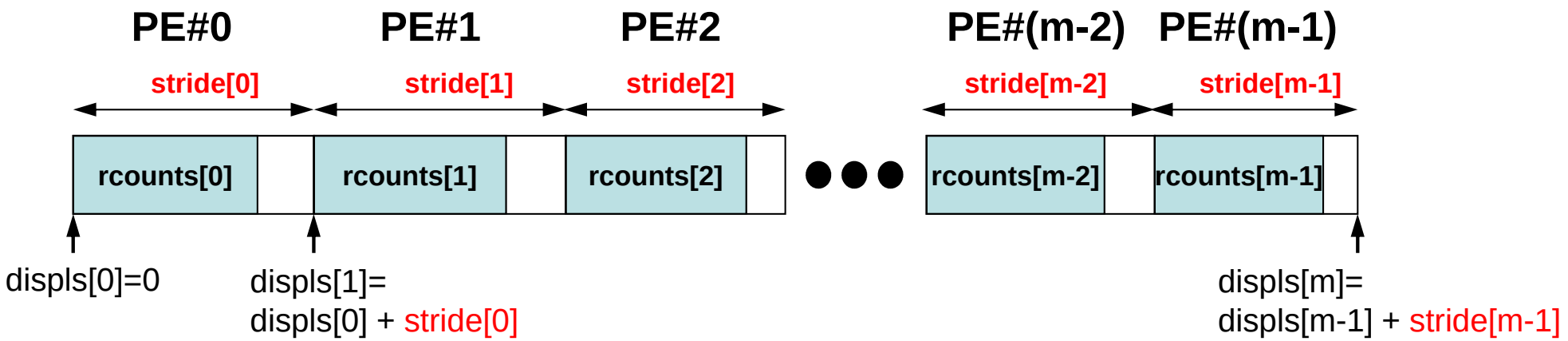


size[recvbuf]= displs[PETOT]= sum[stride]

MPI_Allgatherv in detail (2/2)

C

- Each process needs information of **rcounts** & **displs**
  - **"rcounts"** can be created by gathering local vector length **"N"** from each process.
  - On each process, **"displs"** can be generated from **"rcounts"** on each process.
    - **stride[i]= rcounts[i]**
  - Size of **"recvbuf"** is calculated by summation of **"rcounts"**.



size[recvbuf]= displs[PETOT]= sum[stride]

Preparation for MPI_Allgatherv <$O-S1>/agv.c

- Generating global vector from “a2.0”~”a2.3”.
- Length of the each vector is 8, 5, 7, and 3, respectively. Therefore, size of final global vector is 23 (= 8+5+7+3).

a2.0~a2.3

PE#0

```
   8
101.0
103.0
105.0
106.0
109.0
111.0
121.0
151.0
```

PE#1

```
   5
201.0
203.0
205.0
206.0
209.0
```

PE#2

```
   7
301.0
303.0
305.0
306.0
311.0
321.0
351.0
```

PE#3

```
   3
401.0
403.0
405.0
```

Preparation: MPI_Allgatherv (1/4)

C

<$O-S1>/agv.c

```
int main(int argc, char **argv){
        int i;
        int PeTot, MyRank;
        MPI_Comm SolverComm;
        double *vec, *vec2, *vecg;
        int *Rcounts, *Displs;
        int n;
        double sum0, sum;
        char filename[80];
        FILE *fp;

        MPI_Init(&argc, &argv);
        MPI_Comm_size(MPI_COMM_WORLD, &PeTot);
        MPI_Comm_rank(MPI_COMM_WORLD, &MyRank);

        sprintf(filename, "a2.%d", MyRank);
        fp = fopen(filename, "r");
        assert(fp != NULL);

        fscanf(fp, "%d", &n);
        vec = malloc(n * sizeof(double));
        for(i=0;i<n;i++){
                fscanf(fp, "%lf", &vec[i]);
        }
```

n(NL) is different at each process

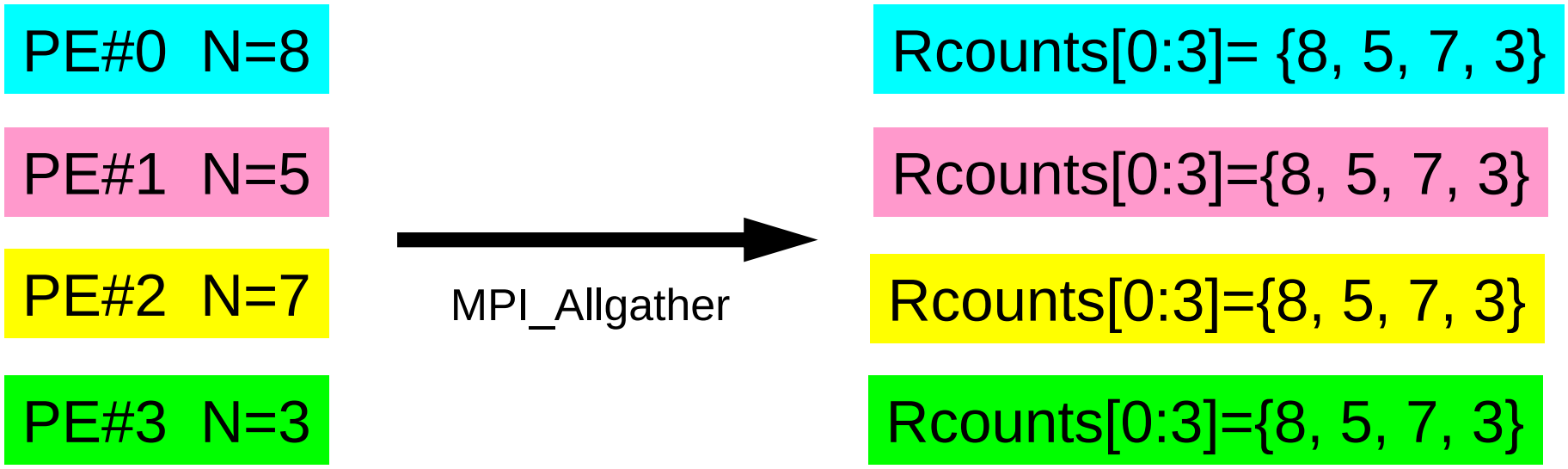
Preparation: MPI_Allgatherv (2/4)

C

<$O-S1>/agv.c

```
Rcounts= calloc(PeTot, sizeof(int));
Displs = calloc(PeTot+1, sizeof(int));

printf("before %d %d", MyRank, n);
for(i=0;i<PeTot;i++){printf(" %d", Rcounts[i]);}

MPI_Allgather(&n, 1, MPI_INT, Rcounts, 1, MPI_INT, MPI_COMM_WORLD);

printf("after  %d %d", MyRank, n);
for(i=0;i<PeTot;i++){printf(" %d", Rcounts[i]);}

Displs[0] = 0;
```

Rcounts on each PE



Preparation: MPI_Allgatherv (2/4)

C

<$O-S1>/agv.c

```
 Rcounts= calloc(PeTot, sizeof(int));
 Displs = calloc(PeTot+1, sizeof(int));

 printf("before %d %d", MyRank, n);
 for(i=0;i<PeTot;i++){printf(" %d", Rcounts[i]);}

 MPI_Allgather(&n, 1, MPI_INT, Rcounts, 1, MPI_INT, MPI_COMM_WORLD);

 printf("after  %d %d", MyRank, n);
 for(i=0;i<PeTot;i++){printf(" %d", Rcounts[i]);}

 Displs[0] = 0;
 for(i=0;i<PeTot;i++){
                 Displs[i+1] = Displs[i] + Rcounts[i];}

         printf("CoundIndex  %d ", MyRank);
         for(i=0;i<PeTot+1;i++){
                 printf(" %d", Displs[i]);
         }
         MPI_Finalize();
         return 0;
}
```

Rcounts on each PE

Displs on each PE

Preparation: MPI_Allgatherv (3/4)

```
> cd /lustre/gt18/t18XXX/pFEM/mpi/S1
> mpicc -O3 agv.c

(modify go4.sh for 4 processes)
> qsub go4.sh


before       0       8       0       0       0       0
after        0       8       8       5       7       3
Displs       0       0       8      13      20      23

before       1       5       0       0       0       0
after        1       5       8       5       7       3
Displs       1       0       8      13      20      23

before       3       3       0       0       0       0
after        3       3       8       5       7       3
Displs       3       0       8      13      20      23

before       2       7       0       0       0       0
after        2       7       8       5       7       3
Displs       2       0       8      13      20      23
```

```
write (*,‘(a,10i8)’) “before”, my_rank, N, rcounts
write (*,'(a,10i8)') "after ", my_rank, N, rcounts
write (*,'(a,10i8)') "displs", my_rank, displs
```

Preparation: MPI_Allgatherv (4/4)

- Only "recvbuf" is not defined yet.
- Size of "recvbuf" = "Displs[PETOT]"

```
MPI_Allgatherv
      ( VEC , N, MPI_DOUBLE,
        recvbuf, rcounts, displs, MPI_DOUBLE,
        MPI_COMM_WORLD);
```

Report S1 (1/2)

- Deadline: January 31st (Tue), 2019, 17:00
  - Send files via e-mail at **nakajima(at)cc.u-tokyo.ac.jp**

- Problem S1-1
  - Read local files <$O-S1>/a1.0~a1.3, <$O-S1>/a2.0~a2.3.
  - Develop codes which calculate norm ||x|| of global vector for each case.
    - <$O-S1>file.c, <$O-S1>file2.c

Report S1 (2/2)

- Problem S1-3
  - Develop parallel program which calculates the following numerical integration using “trapezoidal rule” by MPI_Reduce, MPI_Bcast etc.
  - Measure computation time, and parallel performance

$$\int_0^1 \frac{4}{1+x^2}\,dx$$

- Report
  - Cover Page: Name, ID, and Problem ID (S1) must be written.
  - Less than two pages including figures and tables (A4) for each of three sub-problems
    - Strategy, Structure of the Program, Remarks
  - Source list of the program (if you have bugs)
  - Output list (as small as possible)

Options for Optimization

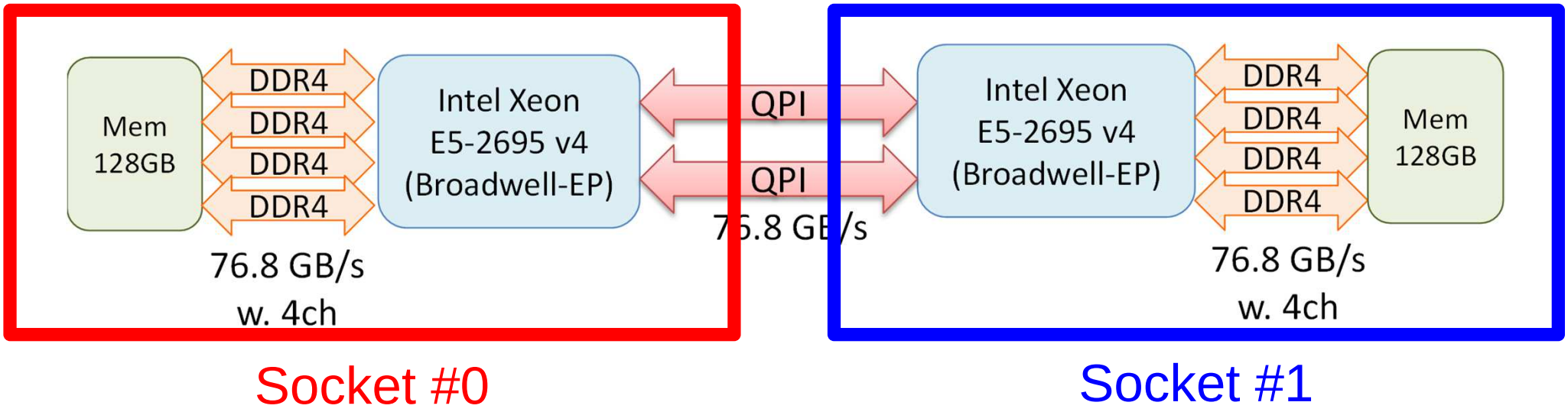
```
$ mpiifort -O3 -xCORE-AVX2 -align array32byte test.f
$ mpicc -O3 -xCORE-AVX2 -align test.c
```

go.sh

```
#!/bin/sh
#PBS -q u-lecture8                      Name of "QUEUE"
#PBS -N test                            Job Name
#PBS -l select=1:mpiprocs=16            node#, proc#/node
#PBS -Wgroup_list=gt18                  Group Name (Wallet)
#PBS -l walltime=00:05:00               Computation Time
#PBS -e err                             Standard Error
#PBS -o test.lst                        Standard Outpt

cd $PBS_O_WORKDIR                       go to current dir
. /etc/profile.d/modules.sh             (ESSENTIAL)

export I_MPI_PIN_DOMAIN=socket          Execution on each socket
export I_MPI_PERHOST=16                 =mpiprocs, stable
mpirun ./impimap.sh ./a.out             Exec's
```

```
#PBS -l select=1:mpiprocs=4     1-node, 4-proc's
#PBS -l select=1:mpiprocs=16    1-node, 16-proc's
#PBS -l select=1:mpiprocs=36    1-node, 36-proc's
#PBS -l select=2:mpiprocs=32    2-nodes, 32x2=64-proc's
#PBS -l select=8:mpiprocs=32    8-nodes, 32x8=256-proc's
#PBS -l select=8:mpiprocs=36    8-nodes, 36x8=288-proc's
```

export I_MPI_PIN_DOMAIN=socket

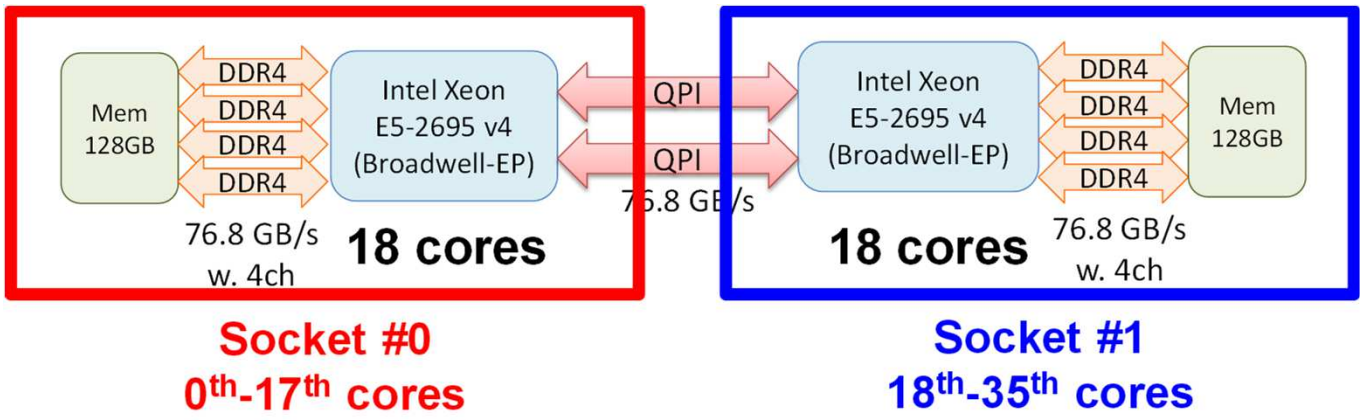


- Each Node of Reedbush-U
  - 2 Sockets (CPU's) of Intel Broadwell-EP
  - Each socket has 18 cores
- Each core of a socket can access to the memory on the other socket : NUMA (Non-Uniform Memory Access)
  - I_MPI_PIN_DOMAIN=socket, impimap.sh: local memory to be used

go.sh

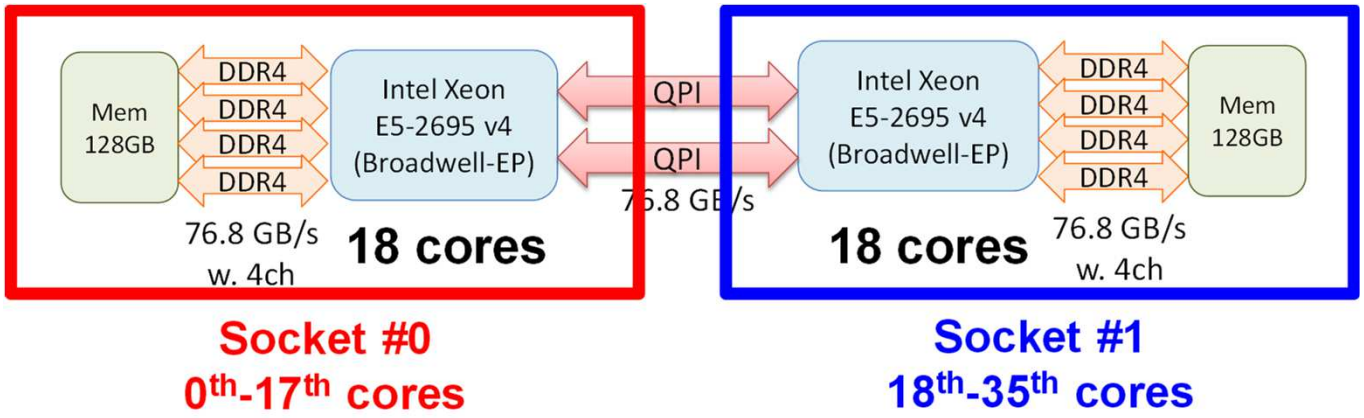
16 cores may be randomly selected from 36 cores

```
#!/bin/sh
#PBS -q u-lecture8                    Name of "QUEUE"
#PBS -N test                          Job Name
#PBS -l select=1:mpiprocs=16          node#, proc#/node
#PBS -Wgroup_list=gt18                Group Name (Wallet)
#PBS -l walltime=00:05:00             Computation Time
#PBS -e err                           Standard Error
#PBS -o test.lst                      Standard Outpt

cd $PBS_O_WORKDIR                     go to current dir
. /etc/profile.d/modules.sh           (ESSENTIAL)

export I_MPI_PIN_DOMAIN=socket        Execution on each socket
export I_MPI_PERHOST=16               =mpiprocs, stable
mpirun ./impimap.sh ./a.out           Exec's
```



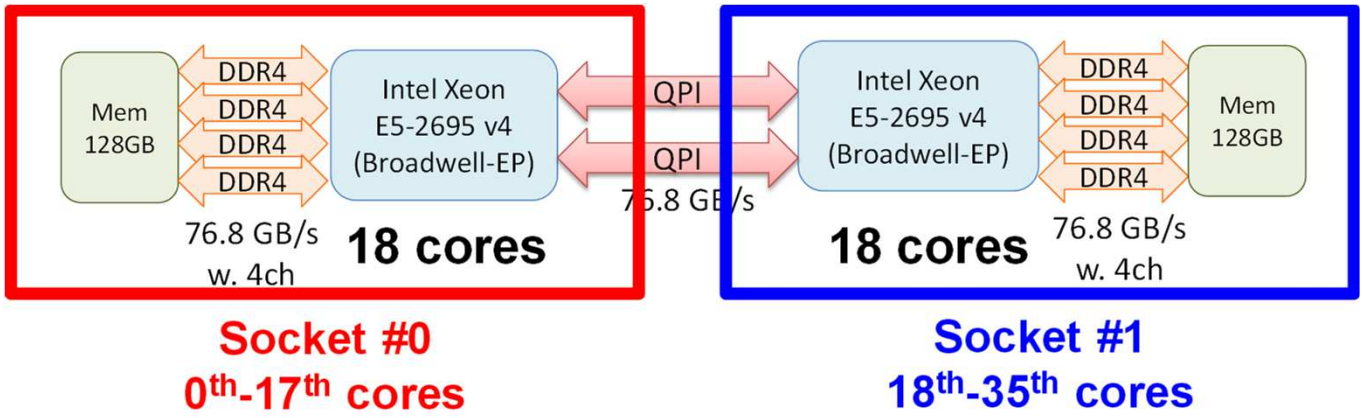
a16.sh: Use 16 cores (0-15th)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=16     MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t16.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0-15   use 0-15th core
mpirun ./impimap.sh ./a.out
```



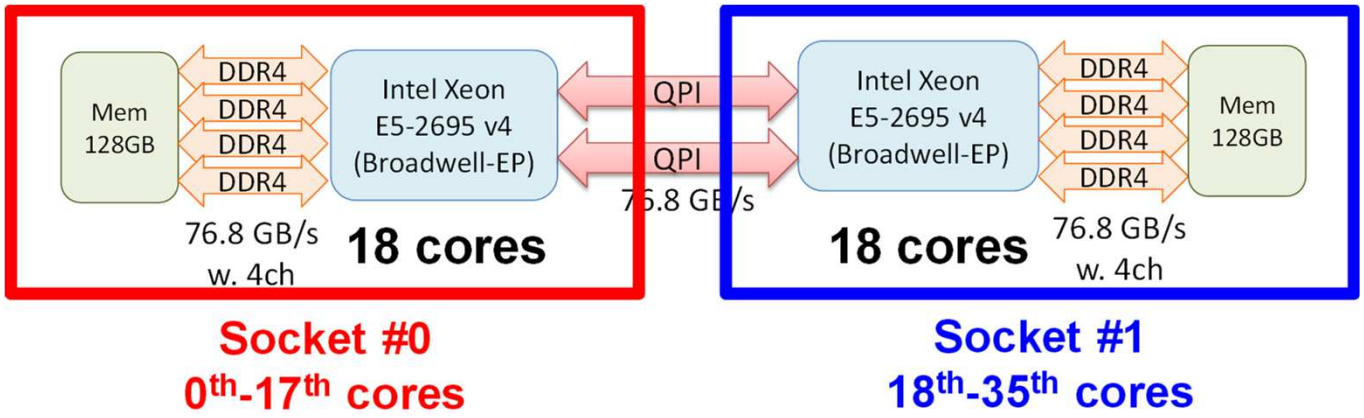
a01.sh: Use 1 core (0th)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=1      MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t01.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0      use 0th core
mpirun ./impimap.sh ./a.out
```



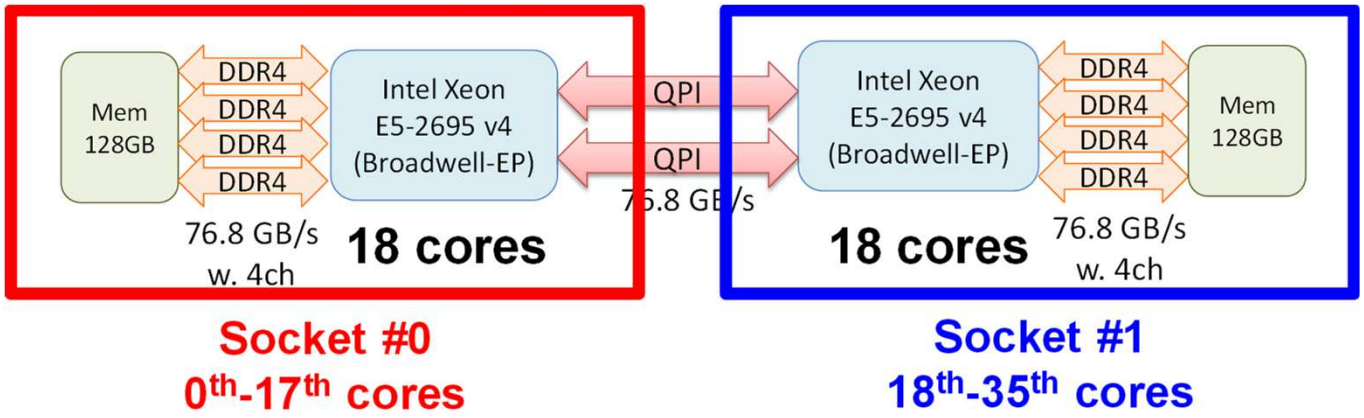
a32.sh: Use 32 cores (16 ea)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=32     MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t32.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0-15,18-33
mpirun ./impimap.sh ./a.out
```



s36.sh: Use 36 cores (ALL)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=36     MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t36.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0-35
mpirun ./impimap.sh ./a.out
```

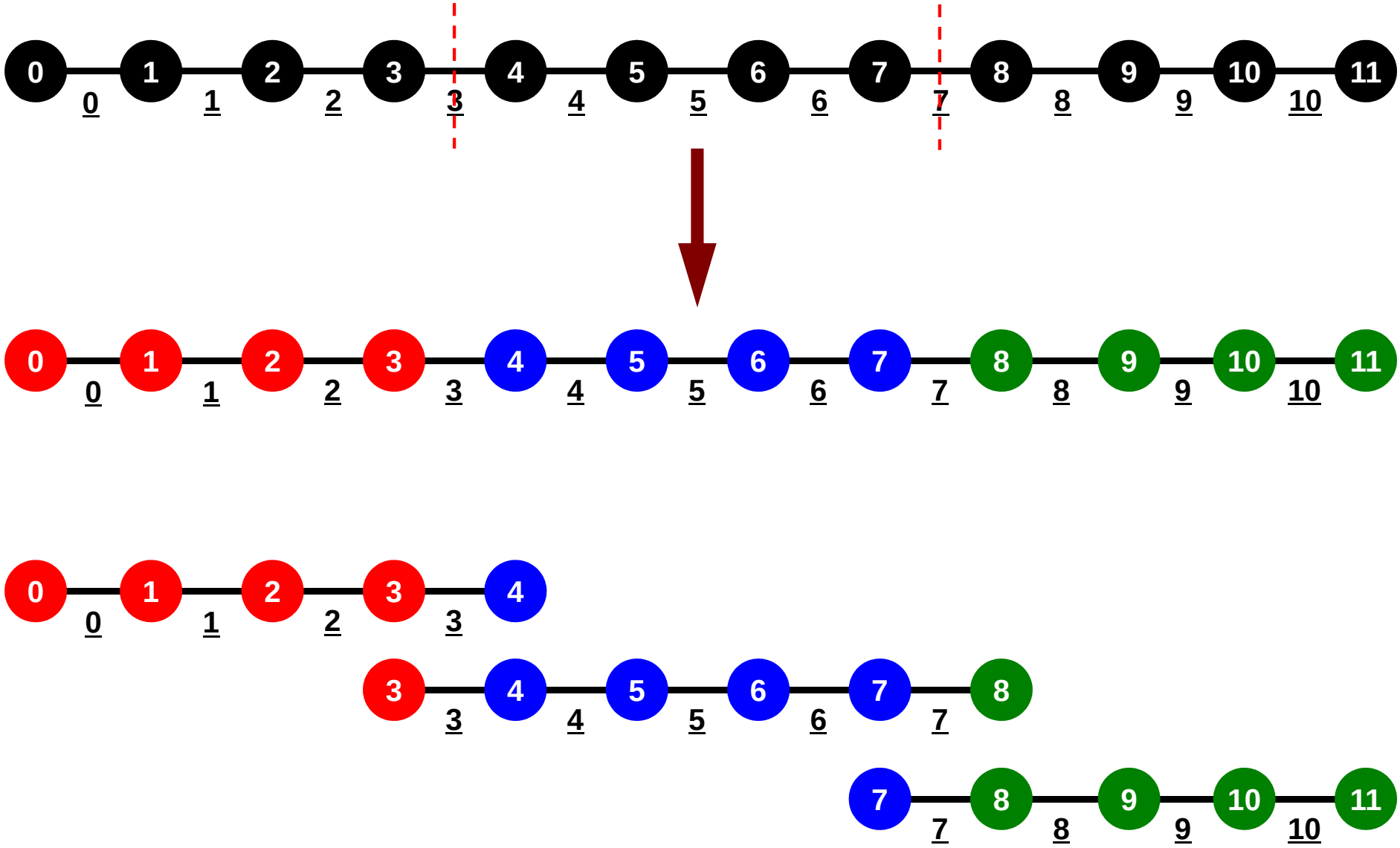


- What is MPI ?
- Your First MPI Program: Hello World
- Collective Communication
- **Point-to-Point Communication**

Point-to-Point Communicatio
1対1通信

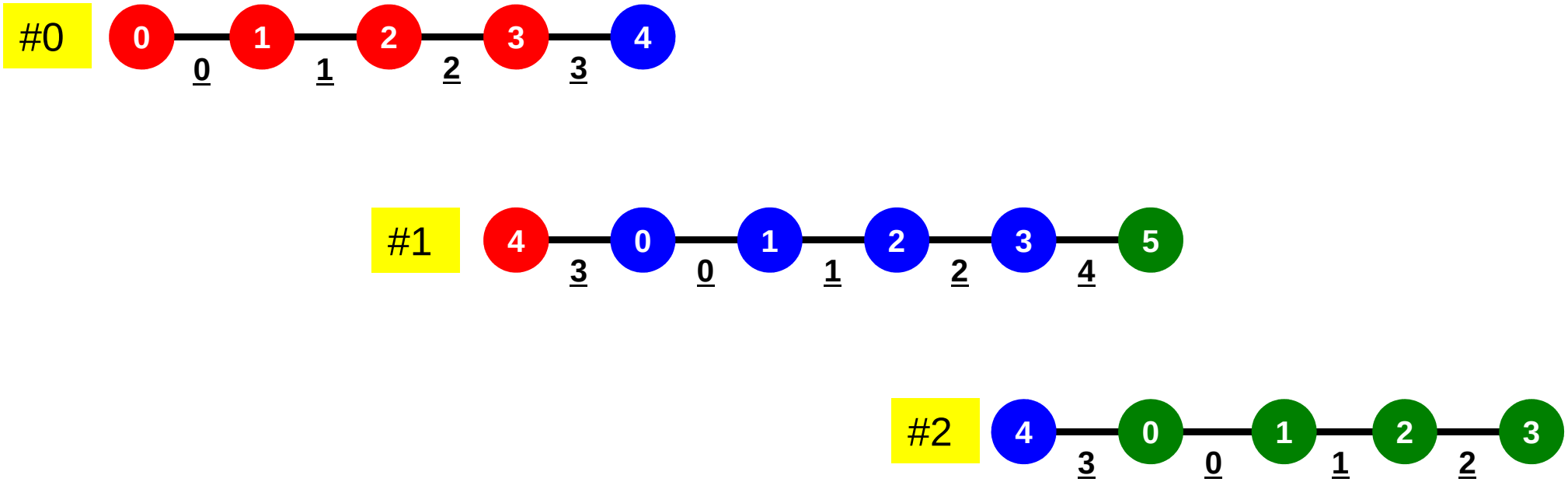
- What is PtoP Communication ?
- 2D Problem, Generalized Communication Table
- Report S2

1D FEM: 12 nodes/11 elem's/3 domains



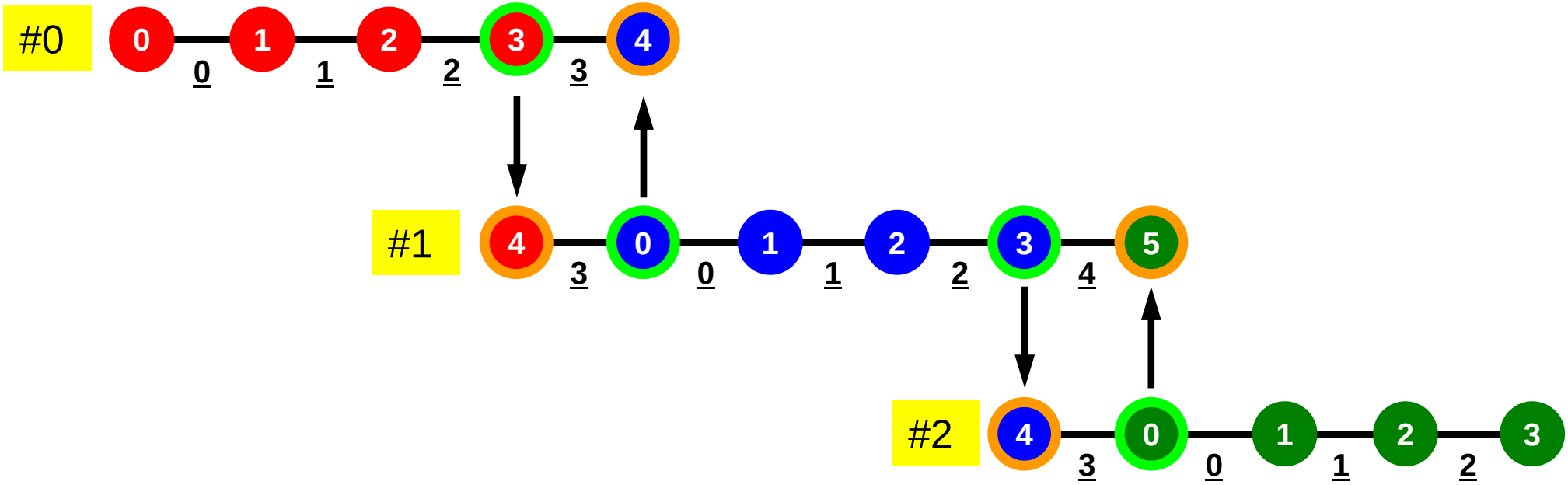
1D FEM: 12 nodes/11 elem's/3 domains

Local ID: Starting from 0 for node and elem at each domain



1D FEM: 12 nodes/11 elem's/3 domains

Internal/External Nodes



Preconditioned Conjugate Gradient Method（CG）

```
Compute r(0)= b-[A]x(0)
for i= 1, 2, …
    solve [M]z(i-1)= r(i-1)
    ρi-1= r(i-1) z(i-1)
    if i=1
      p(1)= z(0)
     else
      βi-1= ρi-1/ρi-2
      p(i)= z(i-1) + βi-1 p(i-1)
    endif
    q(i)= [A]p(i)
    αi  = ρi-1/p(i)q(i)
    x(i)= x(i-1) + αip(i)
    r(i)= r(i-1) – αiq(i)
    check convergence |r|
end
```

Preconditioner:

Diagonal Scaling
Point-Jacobi Preconditioning

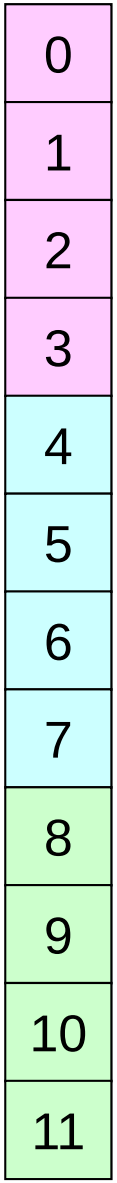
$$[M]=\begin{bmatrix} D_1 & 0 & \dots & 0 & 0 \\ 0 & D_2 & & 0 & 0 \\ \dots & & \dots & & \dots \\ 0 & 0 & & D_{N-1} & 0 \\ 0 & 0 & \dots & 0 & D_N \end{bmatrix}$$

Preconditioning, DAXPY

Local Operations by Only Internal Points: Parallel Processing is possible

```
/*
//-- {z}= [Minv]{r}
*/
        for(i=0;i<N;i++){
          W[Z][i] = W[DD][i] * W[R][i];
        }
```

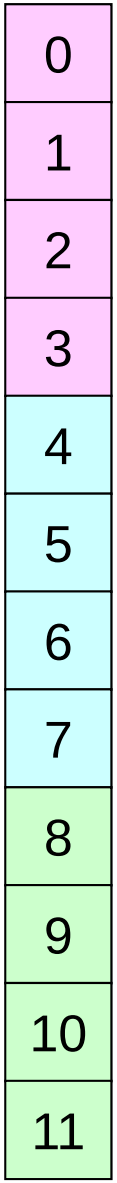
```
/*
//-- {x}= {x} + ALPHA*{p}      DAXPY: double a{x} plus {y}
//   {r}= {r} - ALPHA*{q}
*/
        for(i=0;i<N;i++){
          PHI[i]  += Alpha * W[P][i];
          W[R][i] -= Alpha * W[Q][i];
        }
```



Dot Products

Global Summation needed: Communication ?

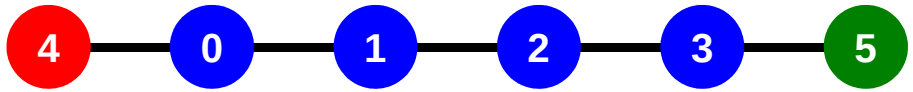
```
/*
//-- ALPHA= RHO / {p}{q}
*/
  C1 = 0.0;
  for(i=0;i<N;i++){
      C1 += W[P][i] * W[Q][i];
  }

  Alpha = Rho / C1;
```



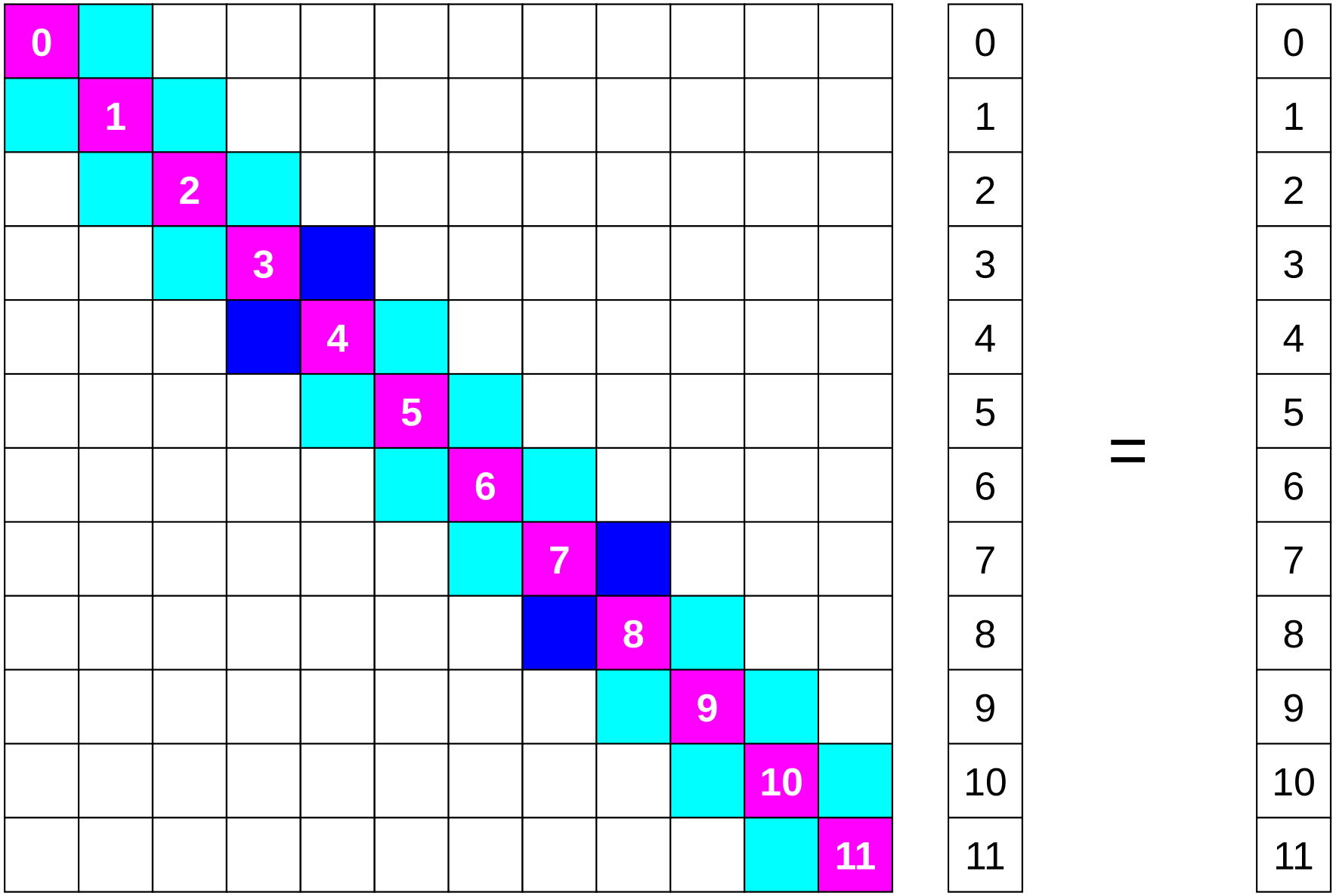
Matrix-Vector Products

Values at External Points: P-to-P Communication

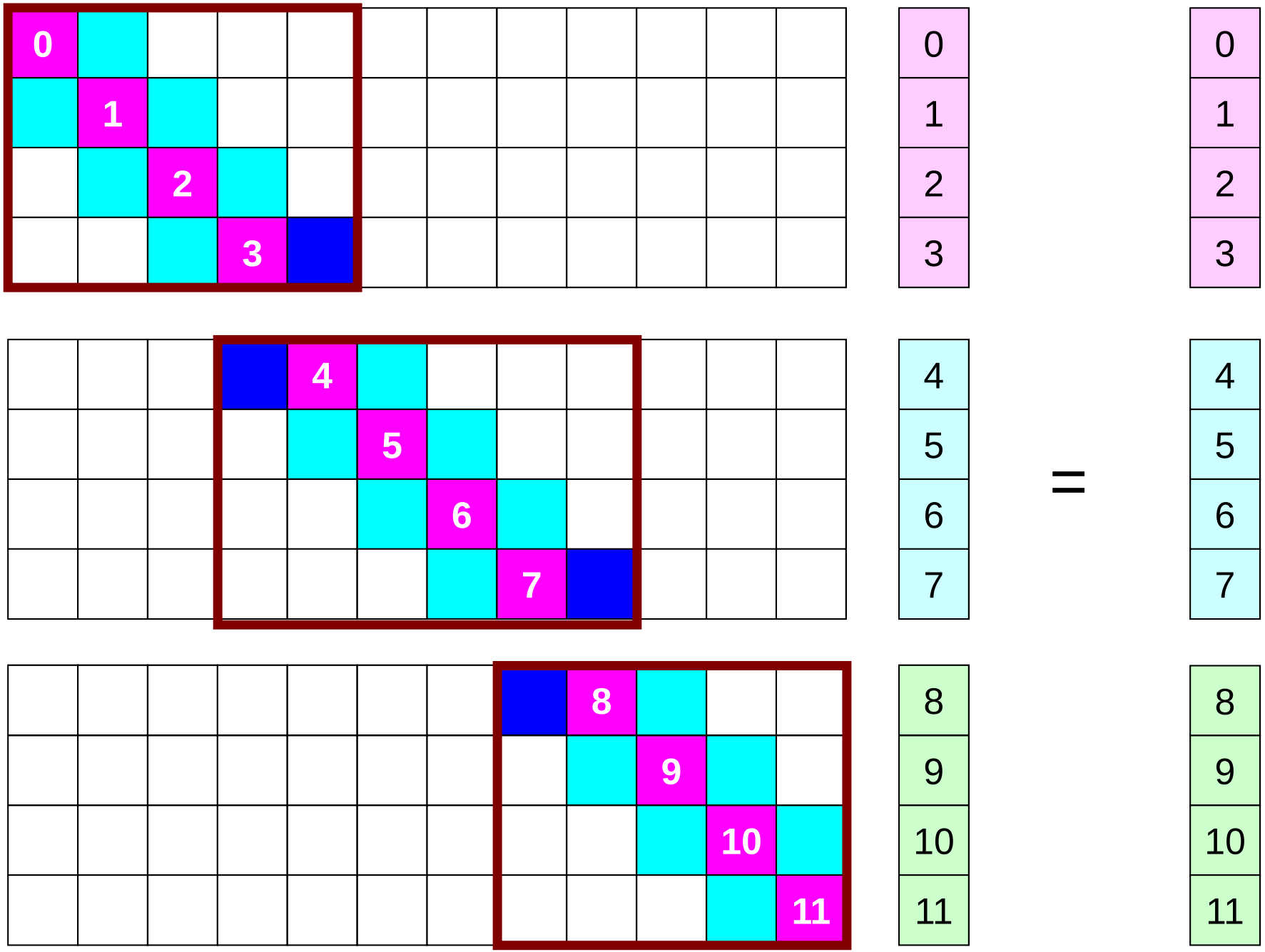
```
/*
//-- {q}= [A]{p}
*/
  for(i=0;i<N;i++){
      W[Q][i] = Diag[i] * W[P][i];
      for(j=Index[i];j<Index[i+1];j++){
          W[Q][i] += AMat[j]*W[P][Item[j]];
          }
      }
```



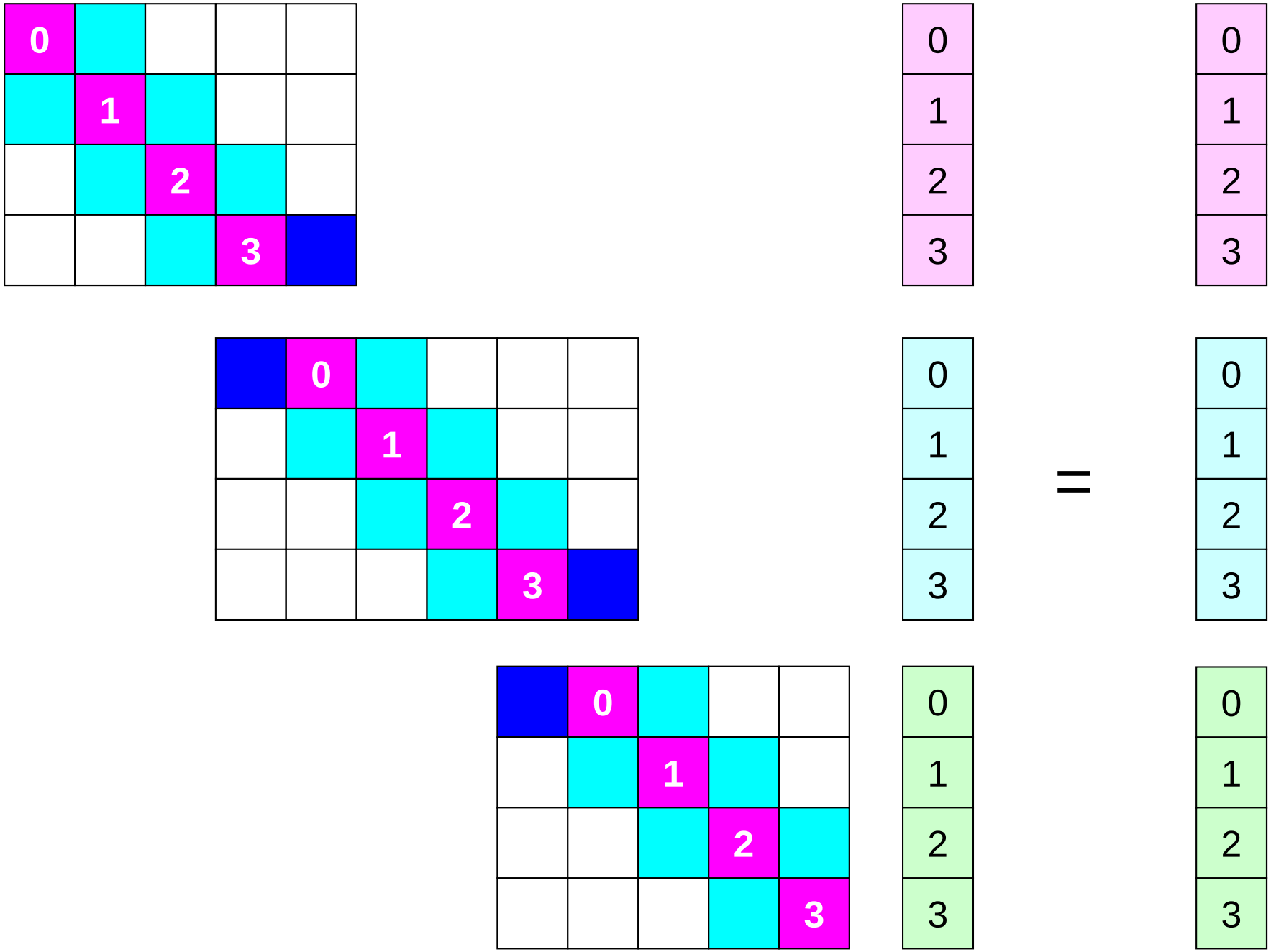
Mat-Vec Products: Local Op. Possible



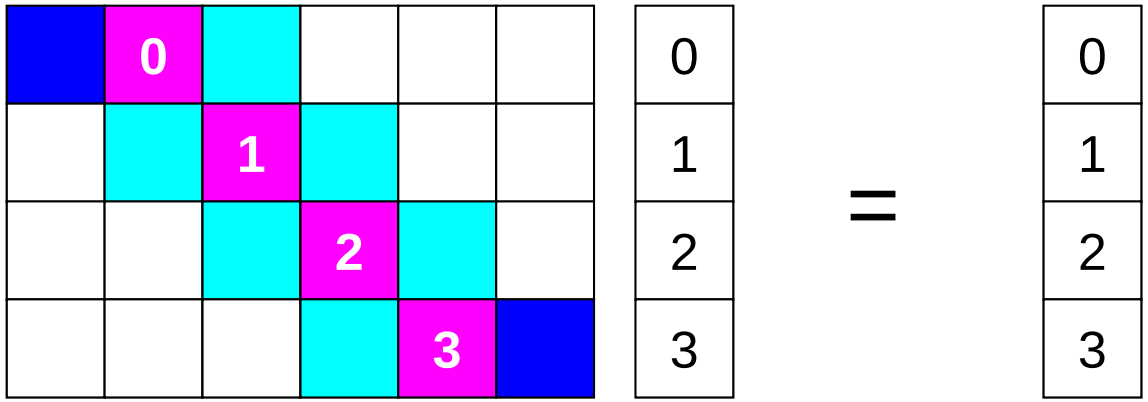
Mat-Vec Products: Local Op. Possible

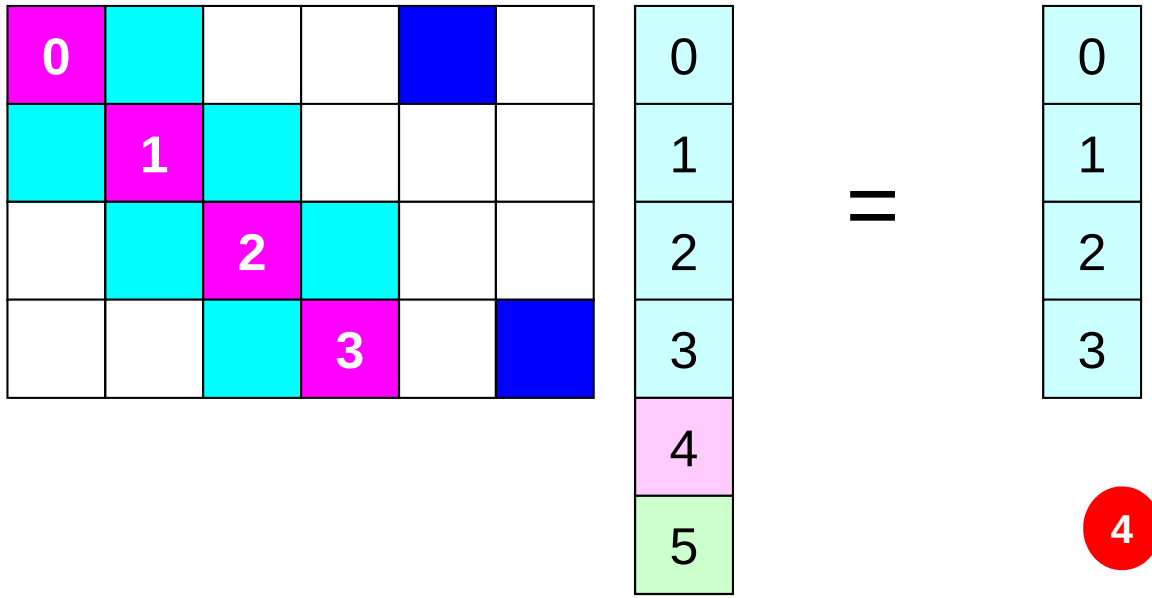


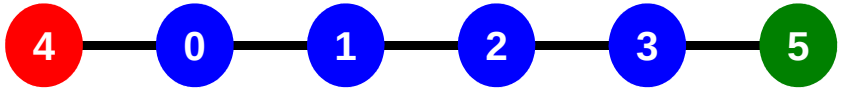
Mat-Vec Products: Local Op. Possible



Mat-Vec Products: Local Op. #1



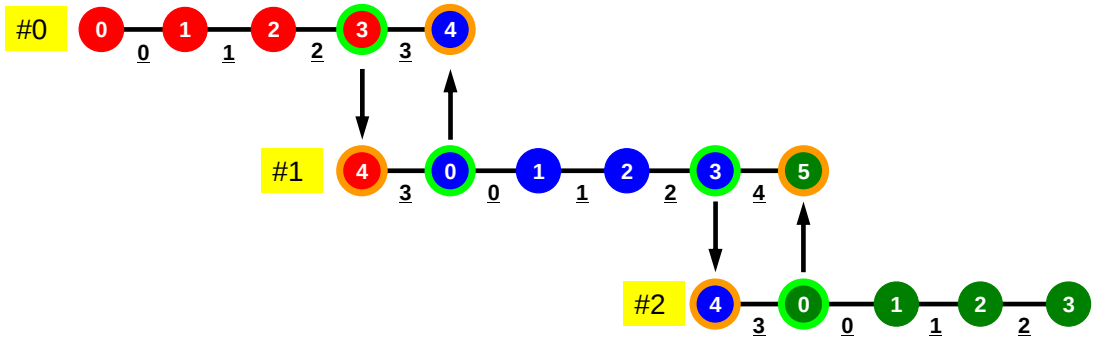




What is Point-to-Point Comm. ?

- Collective Communication
  - MPI_Reduce, MPI_Scatter/Gather etc.
  - Communications with all processes in the communicator
  - Application Area
    - BEM, Spectral Method, MD: global interactions are considered
    - Dot products, MAX/MIN: Global Summation & Comparison

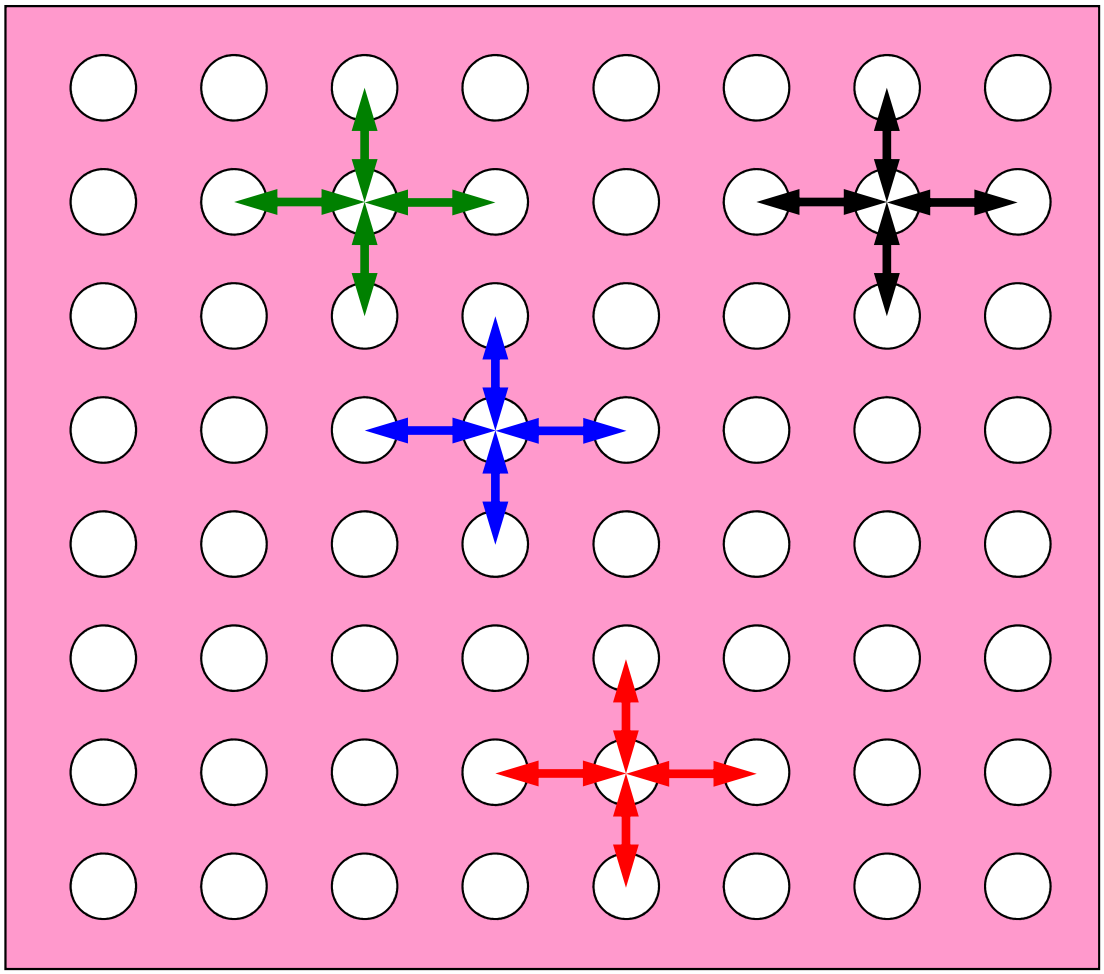
- Point-to-Point
  - MPI_Send, MPI_Recv
  - Communication with limited processes
    - Neighbors
  - Application Area
    - FEM, FDM: Localized Method



Collective/PtoP Communications

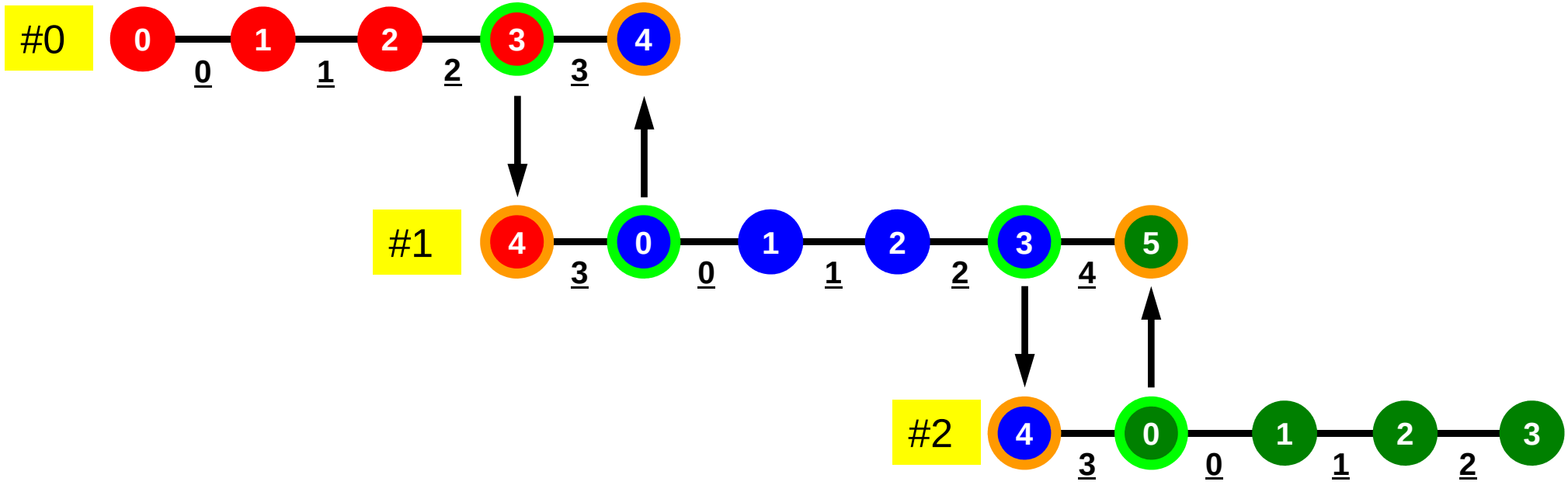
Interactions with only Neighboring Processes/Element

Finite Difference Method (FDM), Finite Element Method (FEM)



When do we need PtoP comm.: 1D-FEM

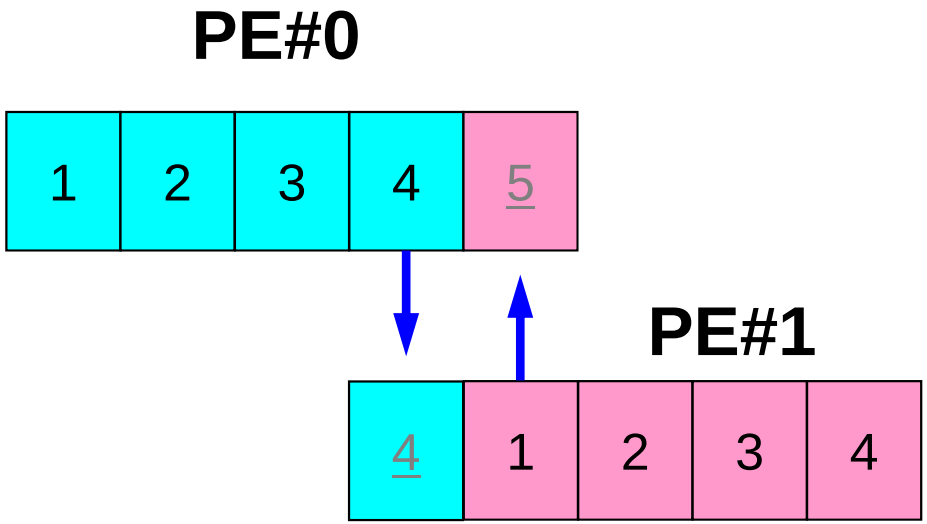
Info in neighboring domains is required for FEM operations
Matrix assembling, Iterative Method



Method for PtoP Comm.

- **`MPI_Send`, `MPI_Recv`**
- These are “blocking” functions. “Dead lock” occurs for these “blocking” functions.
- A “blocking” MPI call means that the program execution will be suspended until the message buffer is safe to use.
- The MPI standards specify that a blocking SEND or RECV does not return until the send buffer is safe to reuse (for MPI_Send), or the receive buffer is ready to use (for MPI_Recv).
  - Blocking comm. confirms “secure” communication, but it is very inconvenient.
- Please just remember that “there are such functions”.

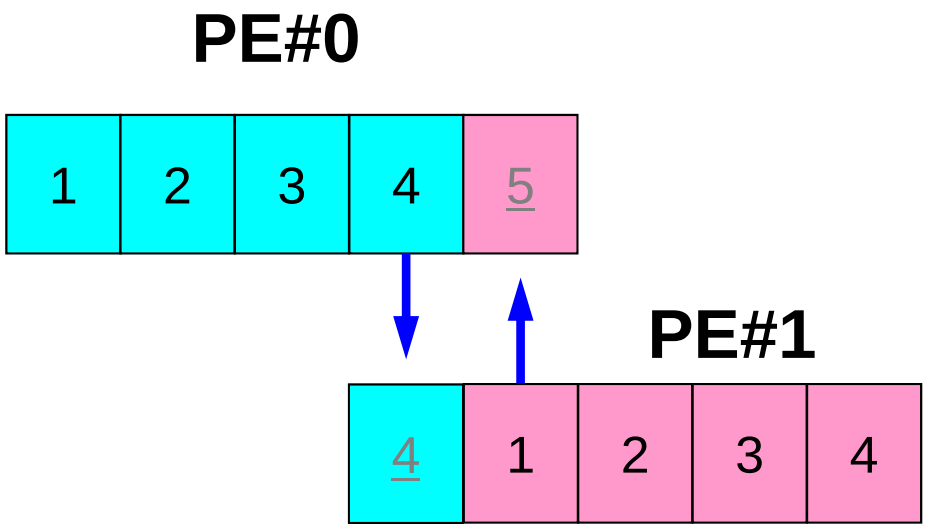
MPI_Send/MPI_Recv




```
if (my_rank.eq.0) NEIB_ID=1
if (my_rank.eq.1) NEIB_ID=0

…
call MPI_SEND (NEIB_ID, arg's)
call MPI_RECV (NEIB_ID, arg's)
…
```

- This seems reasonable, but it stops at MPI_Send/MPI_Recv.
  - Sometimes it works (according to implementation).

MPI_Send/MPI_Recv (cont.)

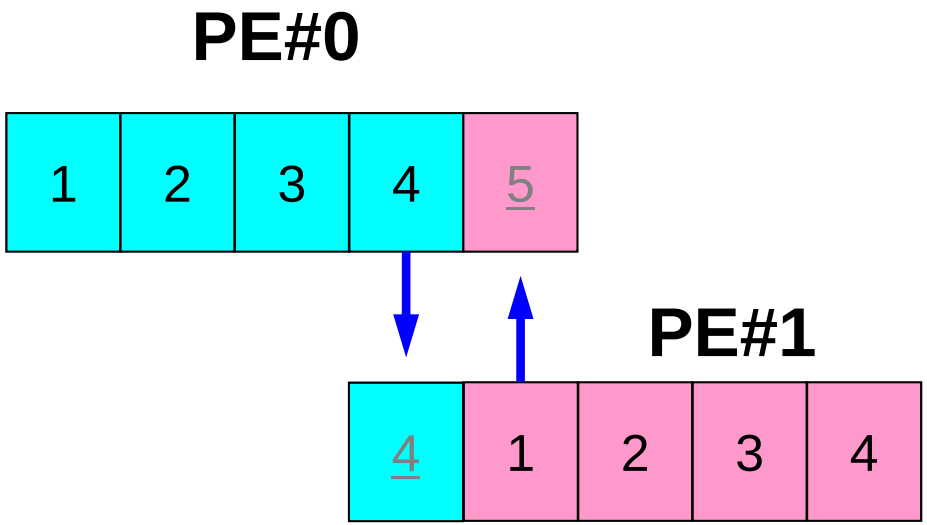



```
if (my_rank.eq.0) NEIB_ID=1
if (my_rank.eq.1) NEIB_ID=0

…
if (my_rank.eq.0) then
  call MPI_SEND (NEIB_ID, arg's)
  call MPI_RECV (NEIB_ID, arg's)
endif

if (my_rank.eq.1) then
  call MPI_RECV (NEIB_ID, arg's)
  call MPI_SEND (NEIB_ID, arg's)
endif

…
```

- It works.
- It is OK for Structured Meshes for FDM (Finite Difference Method).

How to do PtoP Comm. ?

- Using “non-blocking” functions **MPI_Isend** & **MPI_Irecv** together with **MPI_Waitall** for synchronization
- **MPI_Sendrecv** is also available.




```
if (my_rank.eq.0) NEIB_ID=1
if (my_rank.eq.1) NEIB_ID=0

…
call MPI_Isend (NEIB_ID, arg’s)
call MPI_Irecv (NEIB_ID, arg’s)
…
call MPI_Waitall (for Irecv)
…
call MPI_Waitall (for Isend)
```

MPI_Waitall for both of **MPI_Isend/MPI_Irecv** is possible

C

MPI_Isend

- Begins a non-blocking send
  - Send the contents of sending buffer (starting from **sendbuf**, number of messages: **count**) to **dest** with **tag** .
  - Contents of sending buffer cannot be modified before calling corresponding **MPI_Waitall**.

- **MPI_Isend (sendbuf,count,datatype,dest,tag,comm,request)**
  - **sendbuf** choice I starting address of sending buffer
  - **count** int I number of elements in sending buffer
  - **datatype** MPI_Datatype I datatype of each sending buffer element
  - **dest** int I rank of destination
  - **tag** int I message tag
    This integer can be used by the application to distinguish messages. Communication occurs if `tag's` of `MPI_Isend` and `MPI_Irecv` are matched.
    Usually tag is set to be “0” (in this class),
  - **comm** MPI_Comm I communicator
  - **request** MPI_Request O communication request array used in `MPI_Waitall`

Communication Request: request 通信識別子

- **MPI_Isend (sendbuf,count,datatype,dest,tag,comm,request)**
  - **sendbuf** choice I — starting address of sending buffer
  - **count** int I — number of elements in sending buffer
  - **datatype** MPI_Datatype I — datatype of each sending buffer element
  - **dest** int I — rank of destination
  - **tag** int I — message tag
    This integer can be used by the application to distinguish messages. Communication occurs if `tag's` of `MPI_Isend` and `MPI_Irecv` are matched.
    Usually tag is set to be “0” (in this class),
  - **comm** MPI_Comm I — communicator
  - **request** MPI_Request O — communication request used in `MPI_Waitall`
    Size of the array is total number of neighboring processes

- Just define the array

C

C

MPI_Irecv

- Begins a non-blocking receive
  - Receiving the contents of receiving buffer (starting from **`recvbuf`**, number of messages: **`count`**) from **`source`** with **`tag`** .
  - Contents of receiving buffer cannot be used before calling corresponding **`MPI_Waitall`**.

- **`MPI_Irecv`**
  `(recvbuf,count,datatype,source,tag,comm,request)`
  - **`recvbuf`** choice I starting address of receiving buffer
  - **`count`** int I number of elements in receiving buffer
  - **`datatype`** MPI_Datatype I datatype of each receiving buffer element
  - **`source`** int I rank of source
  - **`tag`** int I message tag
    This integer can be used by the application to distinguish messages. Communication occurs if `tag's` of `MPI_Isend` and `MPI_Irecv` are matched.
    Usually tag is set to be “0” (in this class),
  - **`comm`** MPI_Comm I communicator
  - **`request`** MPI_Request O communication request array used in `MPI_Waitall`

MPI_Waitall

C

- **MPI_Waitall** blocks until all comm's, associated with **request** in the array, complete. It is used for synchronizing **MPI_Isend** and **MPI_Irecv** in this class.
- At sending phase, contents of sending buffer cannot be modified before calling corresponding **MPI_Waitall**. At receiving phase, contents of receiving buffer cannot be used before calling corresponding **MPI_Waitall**.
- **MPI_Isend** and **MPI_Irecv** can be synchronized simultaneously with a single **MPI_Waitall** if it is consitent.
  - Same **request** should be used in **MPI_Isend** and **MPI_Irecv**.
- Its operation is similar to that of **MPI_Barrier** but, **MPI_Waitall** can not be replaced by **MPI_Barrier.**
  - Possible troubles using **MPI_Barrier** instead of **MPI_Waitall**: Contents of **request** and **status** are not updated properly, very slow operations etc.

- **MPI_Waitall (count,request,status)**
  - **count** int I number of processes to be synchronized
  - **request** MPI_Request I/O comm. request used in `MPI_Isend/Irecv` (array size: `count`)
  - **status** MPI_Status O array of status objects

    `MPI_STATUS_SIZE: defined in 'mpif.h', 'mpi.h'`

Array of status object：status
状況オブジェクト配列

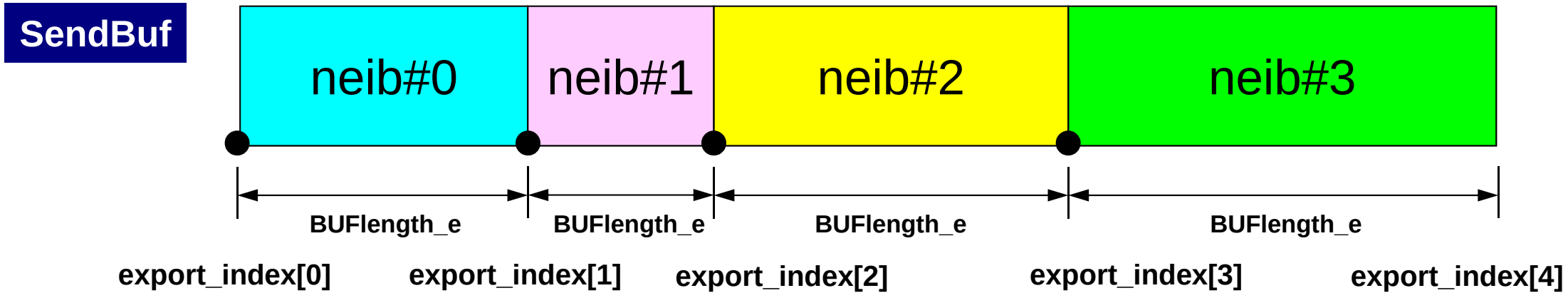
- **`MPI_Waitall (count,request,status)`**
  - **`count`** int I number of processes to be synchronized
  - **`request`** MPI_Request I/O comm. request used in `MPI_Isend/Irecv` (array size: `count`)
  - **`status`** MPI_Status O array of status objects
    `MPI_STATUS_SIZE: defined in 'mpif.h', 'mpi.h'`

- Just define the array

C

SEND: MPI_Isend/Irecv/Waitall

C



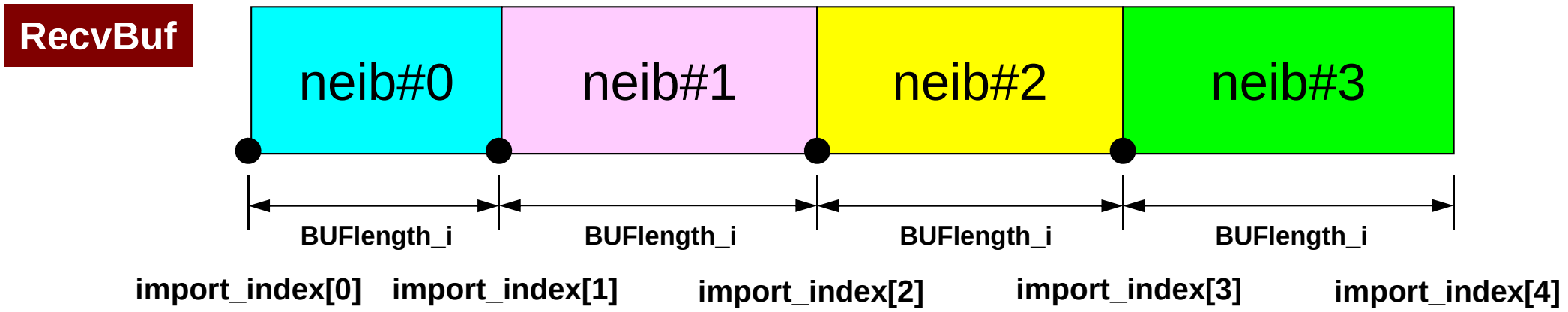

```
for (neib=0; neib<NeibPETot; neib++){
  tag= 0;
  iS_e= export_index[neib];
  iE_e= export_index[neib+1];
  BUFlength_e= iE_e - iS_e

  ierr= MPI_Isend
        (&SendBuf[iS_e], BUFlength_e, MPI_DOUBLE,
                NeibPE[neib], 0,
          MPI_COMM_WORLD, &ReqSend[neib])
}

MPI_Waitall(NeibPETot, ReqSend, StatSend);
```

RECV: MPI_Isend/Irecv/Waitall

C

```
for (neib=0; neib<NeibPETot; neib++){
    tag= 0;
    iS_i= import_index[neib];
    iE_i= import_index[neib+1];
    BUFlength_i= iE_i - iS_i

    ierr= MPI_Irecv
            (&RecvBuf[iS_i], BUFlength_i, MPI_DOUBLE,
              NeibPE[neib], 0,
              MPI_COMM_WORLD, &ReqRecv[neib])
}

MPI_Waitall(NeibPETot, ReqRecv, StatRecv);
```

import_item (import_index[neib]:import_index[neib+1]-1) are received from neib-th neighbor



C

MPI_Sendrecv

- MPI_Send+MPI_Recv: not recommended, many restrictions

- **MPI_Sendrecv (sendbuf,sendcount,sendtype,dest,sendtag,recvbuf, recvcount,recvtype,source,recvtag,comm,status)**
  - **sendbuf** choice I starting address of sending buffer
  - **sendcount** int I number of elements in sending buffer
  - **sendtype** MPI_Datatype I datatype of each sending buffer element
  - **dest** int I rank of destination
  - **sendtag** int I message tag for sending
  - **comm** MPI_Comm I communicator
  - **recvbuf** choice I starting address of receiving buffer
  - **recvcount** int I number of elements in receiving buffer
  - **recvtype** MPI_Datatype I datatype of each receiving buffer element
  - **source** int I rank of source
  - **recvtag** int I message tag for receiving
  - **comm** MPI_Comm I communicator
  - **status** MPI_Status O array of status objects

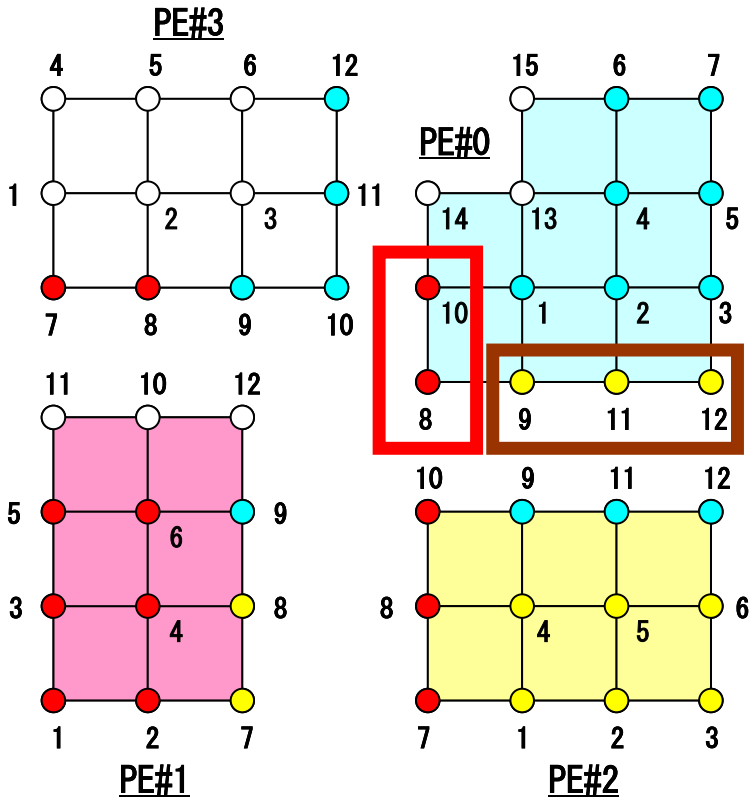
    `MPI_STATUS_SIZE: defined in 'mpif.h', 'mpi.h'`

RECV: receiving to external nodes

Recv. continuous data to recv. buffer from neighbors

- **`MPI_Irecv`**
  `(recvbuf,count,datatype,source,tag,comm,request)`

`recvbuf`	choice	I	starting address of receiving buffer
`count`	int	I	number of elements in receiving buffer
`datatype`	MPI_Datatype	I	datatype of each receiving buffer element
`source`	int	I	rank of source

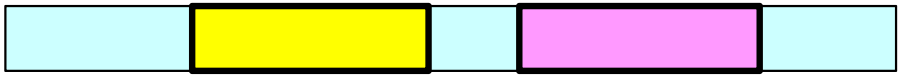


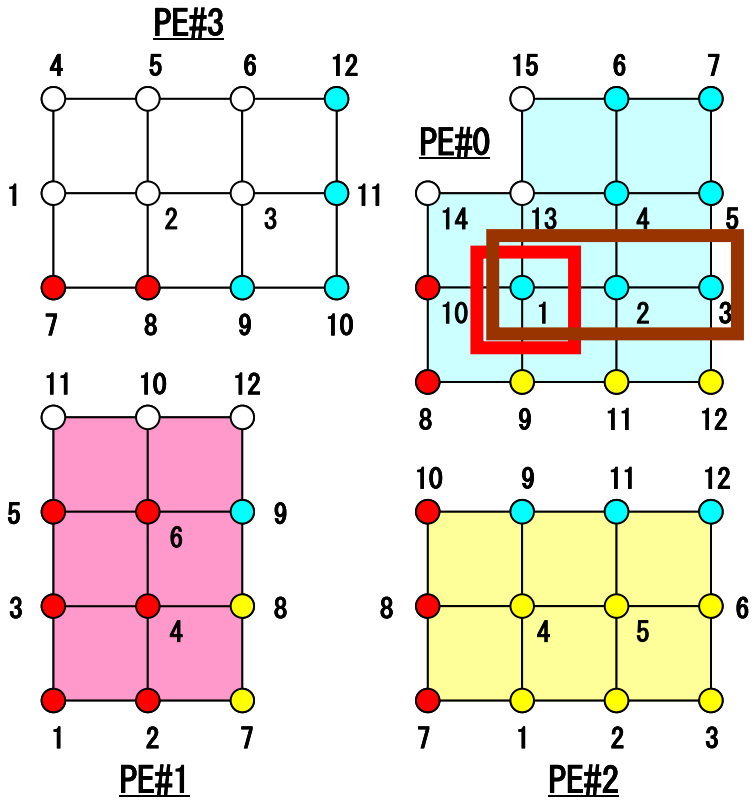
SEND: sending from boundary nodes

Send continuous data to send buffer of neighbors

- **`MPI_Isend`**
  `(sendbuf,count,datatype,dest,tag,comm,request)`

`sendbuf`	choice	I	starting address of sending buffer
`count`	int	I	number of elements in sending buffer
`datatype`	MPI_Datatype	I	datatype of each sending buffer element
`dest`	int	I	rank of destination





Request, Status in C Language Special TYPE of Arrays

- **MPI_Isend: request**
- **MPI_Irecv: request**
- **MPI_Waitall: request, status**

```
MPI_Status  *StatSend, *StatRecv;
MPI_Request *RequestSend, *RequestRecv;
...
StatSend = malloc(sizeof(MPI_Status) * NEIBpetot);
StatRecv = malloc(sizeof(MPI_Status) * NEIBpetot);
RequestSend = malloc(sizeof(MPI_Request) * NEIBpetot);
RequestRecv = malloc(sizeof(MPI_Request) * NEIBpetot);
```

- **MPI_Sendrecv: status**

```
MPI_Status *Status;
...
Status = malloc(sizeof(MPI_Status));
```

Files on Reedbush-U

Fotran

```
>$ cdw
>$ cd pFEM
>$ cp /luster/gt00/z30088/class_eps/F/s2-f.tar .
>$ tar xvf s2-f.tar
```

C

```
>$ cdw
>$ cd pFEM
>$ cp /lustre/gt16/z30088/class_eps/C/s2-c.tar .
>$ tar xvf s2-c.tar
```

Confirm Directory

```
>$ ls
   mpi

>$ cd mpi/S2
```

This directory is called as <$O-S2> in this course.

<$O-S2> = <$O-TOP>/mpi/S2

Ex.1: Send-Recv a Scalar

- Exchange VAL (real, 8-byte) between PE#0 & PE#1

```
if (my_rank.eq.0) NEIB= 1
if (my_rank.eq.1) NEIB= 0

call MPI_Isend (VAL    ,1,MPI_DOUBLE_PRECISION,NEIB,…,req_send,…)
call MPI_Irecv (VALtemp,1,MPI_DOUBLE_PRECISION,NEIB,…,req_recv,…)
call MPI_Waitall (…,req_recv,stat_recv,…): Recv.buf VALtemp can be used
call MPI_Waitall (…,req_send,stat_send,…): Send buf VAL can be modified
VAL= VALtemp
```

```
if (my_rank.eq.0) NEIB= 1
if (my_rank.eq.1) NEIB= 0

call MPI_Sendrecv (VAL    ,1,MPI_DOUBLE_PRECISION,NEIB,…              &
                   VALtemp,1,MPI_DOUBLE_PRECISION,NEIB,…, status,…)
VAL= VALtemp
```

Name of recv. buffer could be "VAL", but not recommended.

Ex.1: Send-Recv a Scalar

Isend/Irecv/Waitall

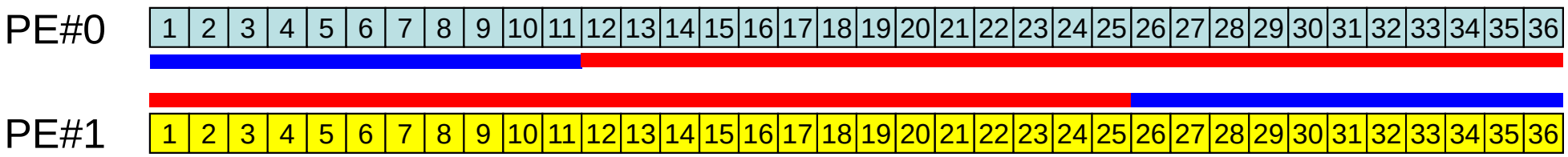
```
$> cd /lustre/gt18/t18XXX/pFEM/mpi/S2
$> mpicc -O3 ex1-1.c
$> qsub go2.sh
```

```
#include <stdio.h>
#include <stdlib.h>
#include "mpi.h"
int main(int argc, char **argv){
        int neib, MyRank, PeTot;
        double VAL, VALx;
        MPI_Status *StatSend, *StatRecv;
        MPI_Request *RequestSend, *RequestRecv;

        MPI_Init(&argc, &argv);
        MPI_Comm_size(MPI_COMM_WORLD, &PeTot);
        MPI_Comm_rank(MPI_COMM_WORLD, &MyRank);
        StatSend = malloc(sizeof(MPI_Status) * 1);
        StatRecv = malloc(sizeof(MPI_Status) * 1);
        RequestSend = malloc(sizeof(MPI_Request) * 1);
        RequestRecv = malloc(sizeof(MPI_Request) * 1);

        if(MyRank == 0) {neib= 1; VAL= 10.0;}
        if(MyRank == 1) {neib= 0; VAL= 11.0;}

        MPI_Isend(&VAL , 1, MPI_DOUBLE, neib, 0, MPI_COMM_WORLD, &RequestSend[0]);
        MPI_Irecv(&VALx, 1, MPI_DOUBLE, neib, 0, MPI_COMM_WORLD, &RequestRecv[0]);
        MPI_Waitall(1, RequestRecv, StatRecv);
        MPI_Waitall(1, RequestSend, StatSend);

        VAL=VALx;
        MPI_Finalize();
        return 0; }
```

Ex.2: Send-Recv an Array (1/3)

- Exchange VEC (real, 8-byte) between PE#0 & PE#1
- PE#0 to PE#1
  - PE#0: send VEC(1)-VEC(11) (length=11)
  - PE#1: recv. as VEC(26)-VEC(36) (length=11)
- PE#1 to PE#0
  - PE#1: send VEC(1)-VEC(25) (length=25)
  - PE#0: recv. as VEC(12)-VEC(36) (length=25)

- Practice: Develop a program for this operation.



t1

Practice: t1

- Initial status of VEC[:]:
  - PE#0 VEC[0-35]= 101,102,103,~,135,136
  - PE#1 VEC[0-35]= 201,202,203,~,235,236
- Confirm the results in the next page
- MPI_Isend/Irecv/Waitall

Estimated Results

t1

```
0 #BEFORE#  1      101.
0 #BEFORE#  2      102.
0 #BEFORE#  3      103.
0 #BEFORE#  4      104.
0 #BEFORE#  5      105.
0 #BEFORE#  6      106.
0 #BEFORE#  7      107.
0 #BEFORE#  8      108.
0 #BEFORE#  9      109.
0 #BEFORE# 10      110.
0 #BEFORE# 11      111.
0 #BEFORE# 12      112.
0 #BEFORE# 13      113.
0 #BEFORE# 14      114.
0 #BEFORE# 15      115.
0 #BEFORE# 16      116.
0 #BEFORE# 17      117.
0 #BEFORE# 18      118.
0 #BEFORE# 19      119.
0 #BEFORE# 20      120.
0 #BEFORE# 21      121.
0 #BEFORE# 22      122.
0 #BEFORE# 23      123.
0 #BEFORE# 24      124.
0 #BEFORE# 25      125.
0 #BEFORE# 26      126.
0 #BEFORE# 27      127.
0 #BEFORE# 28      128.
0 #BEFORE# 29      129.
0 #BEFORE# 30      130.
0 #BEFORE# 31      131.
0 #BEFORE# 32      132.
0 #BEFORE# 33      133.
0 #BEFORE# 34      134.
0 #BEFORE# 35      135.
0 #BEFORE# 36      136.
```

```
0 #AFTER #  1      101.
0 #AFTER #  2      102.
0 #AFTER #  3      103.
0 #AFTER #  4      104.
0 #AFTER #  5      105.
0 #AFTER #  6      106.
0 #AFTER #  7      107.
0 #AFTER #  8      108.
0 #AFTER #  9      109.
0 #AFTER # 10      110.
0 #AFTER # 11      111.
0 #AFTER # 12      201.
0 #AFTER # 13      202.
0 #AFTER # 14      203.
0 #AFTER # 15      204.
0 #AFTER # 16      205.
0 #AFTER # 17      206.
0 #AFTER # 18      207.
0 #AFTER # 19      208.
0 #AFTER # 20      209.
0 #AFTER # 21      210.
0 #AFTER # 22      211.
0 #AFTER # 23      212.
0 #AFTER # 24      213.
0 #AFTER # 25      214.
0 #AFTER # 26      215.
0 #AFTER # 27      216.
0 #AFTER # 28      217.
0 #AFTER # 29      218.
0 #AFTER # 30      219.
0 #AFTER # 31      220.
0 #AFTER # 32      221.
0 #AFTER # 33      222.
0 #AFTER # 34      223.
0 #AFTER # 35      224.
0 #AFTER # 36      225.
```

```
1 #BEFORE#  1      201.
1 #BEFORE#  2      202.
1 #BEFORE#  3      203.
1 #BEFORE#  4      204.
1 #BEFORE#  5      205.
1 #BEFORE#  6      206.
1 #BEFORE#  7      207.
1 #BEFORE#  8      208.
1 #BEFORE#  9      209.
1 #BEFORE# 10      210.
1 #BEFORE# 11      211.
1 #BEFORE# 12      212.
1 #BEFORE# 13      213.
1 #BEFORE# 14      214.
1 #BEFORE# 15      215.
1 #BEFORE# 16      216.
1 #BEFORE# 17      217.
1 #BEFORE# 18      218.
1 #BEFORE# 19      219.
1 #BEFORE# 20      220.
1 #BEFORE# 21      221.
1 #BEFORE# 22      222.
1 #BEFORE# 23      223.
1 #BEFORE# 24      224.
1 #BEFORE# 25      225.
1 #BEFORE# 26      226.
1 #BEFORE# 27      227.
1 #BEFORE# 28      228.
1 #BEFORE# 29      229.
1 #BEFORE# 30      230.
1 #BEFORE# 31      231.
1 #BEFORE# 32      232.
1 #BEFORE# 33      233.
1 #BEFORE# 34      234.
1 #BEFORE# 35      235.
1 #BEFORE# 36      236.
```

```
1 #AFTER #  1      201.
1 #AFTER #  2      202.
1 #AFTER #  3      203.
1 #AFTER #  4      204.
1 #AFTER #  5      205.
1 #AFTER #  6      206.
1 #AFTER #  7      207.
1 #AFTER #  8      208.
1 #AFTER #  9      209.
1 #AFTER # 10      210.
1 #AFTER # 11      211.
1 #AFTER # 12      212.
1 #AFTER # 13      213.
1 #AFTER # 14      214.
1 #AFTER # 15      215.
1 #AFTER # 16      216.
1 #AFTER # 17      217.
1 #AFTER # 18      218.
1 #AFTER # 19      219.
1 #AFTER # 20      220.
1 #AFTER # 21      221.
1 #AFTER # 22      222.
1 #AFTER # 23      223.
1 #AFTER # 24      224.
1 #AFTER # 25      225.
1 #AFTER # 26      101.
1 #AFTER # 27      102.
1 #AFTER # 28      103.
1 #AFTER # 29      104.
1 #AFTER # 30      105.
1 #AFTER # 31      106.
1 #AFTER # 32      107.
1 #AFTER # 33      108.
1 #AFTER # 34      109.
1 #AFTER # 35      110.
1 #AFTER # 36      111.
```

t1

Ex.2: Send-Recv an Array (2/3)

```
if (my_rank.eq.0) then
  call MPI_Isend (VEC( 1),11,MPI_DOUBLE_PRECISION,1,…,req_send,…)
  call MPI_Irecv (VEC(12),25,MPI_DOUBLE_PRECISION,1,…,req_recv,…)
endif

if (my_rank.eq.1) then
  call MPI_Isend (VEC( 1),25,MPI_DOUBLE_PRECISION,0,…,req_send,…)
  call MPI_Irecv (VEC(26),11,MPI_DOUBLE_PRECISION,0,…,req_recv,…)
endif

call MPI_Waitall (…,req_recv,stat_recv,…)
call MPI_Waitall (…,req_send,stat_send,…)
```

It works, but complicated operations.
Not looks like SPMD.
Not portable.

t1

Ex.2: Send-Recv an Array (3/3)

```
if (my_rank.eq.0) then
  NEIB= 1
   start_send=   1
  length_send=  11
   start_recv=  length_send + 1
  length_recv=  25
endif

if (my_rank.eq.1) then
  NEIB= 0
   start_send=  1
  length_send= 25
   start_recv= length_send + 1
  length_recv= 11
endif

call MPI_Isend                                                    &
(VEC(start_send),length_send,MPI_DOUBLE_PRECISION,NEIB,…,req_send[0],…)
call MPI_Irecv                                                    &
(VEC(start_recv),length_recv,MPI_DOUBLE_PRECISION,NEIB,…,req_recv[1],…)

call MPI_Waitall (…,req_recv,stat_recv,…)
call MPI_Waitall (…,req_send,stat_send,…)
```

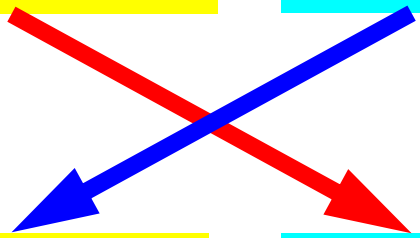
This is “SMPD” !!

t1

Notice: Send/Recv Arrays

```
#PE0
  send:
    VEC(start_send)~
    VEC(start_send+length_send-1)
```

```
#PE1
  send:
    VEC(start_send)~
    VEC(start_send+length_send-1)
```



```
#PE0
  recv:
    VEC(start_recv)~
    VEC(start_recv+length_recv-1)
```

```
#PE1
  recv:
    VEC(start_recv)~
    VEC(start_recv+length_recv-1)
```

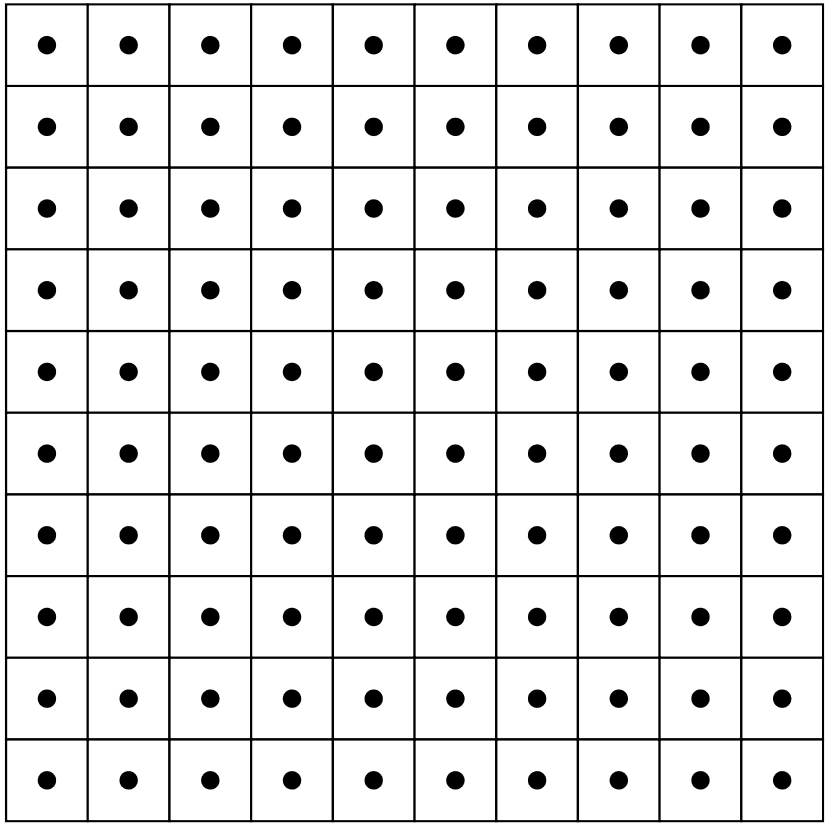
- “length_send” of sending process must be equal to “length_recv” of receiving process.
  - PE#0 to PE#1, PE#1 to PE#0
- “sendbuf” and “recvbuf”: different address

Point-to-Point Communication

- What is PtoP Communication ?
- 2D Problem, Generalized Communication Table
  - 2D FDM
  - Problem Setting
  - Distributed Local Data and Communication Table
  - Implementation
- Report S2

2D FDM (1/5)

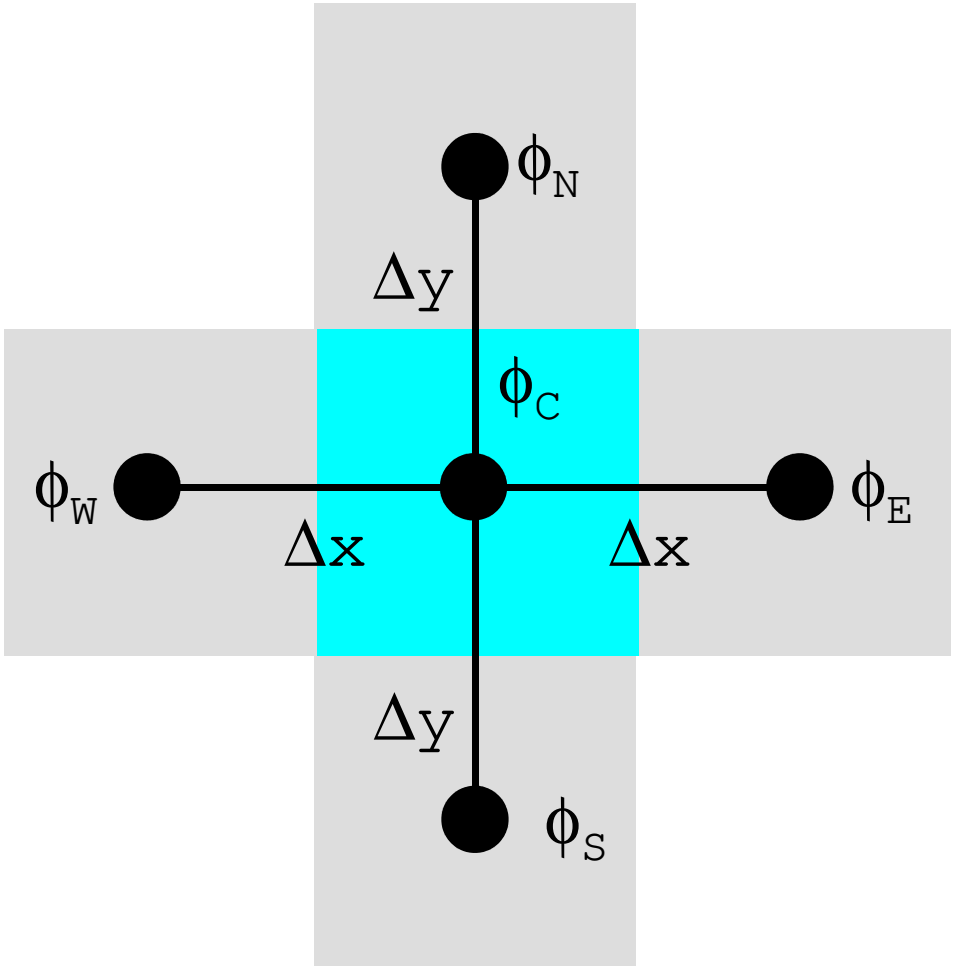
Entire Mesh



2D FDM (5-point, central difference)

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = f$$

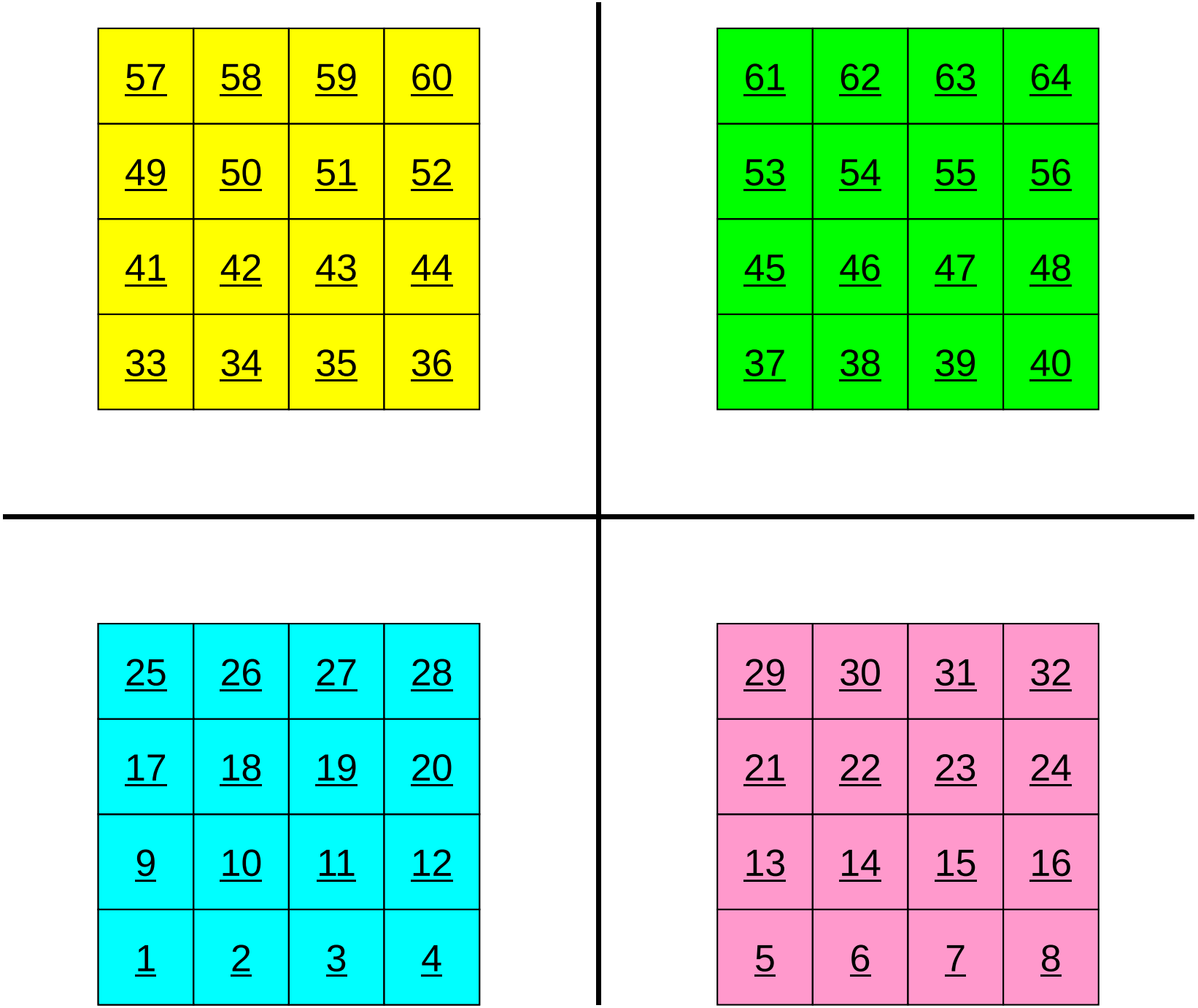
$$\left(\frac{\phi_E - 2\phi_C + \phi_W}{\Delta x^2} \right) + \left(\frac{\phi_N - 2\phi_C + \phi_S}{\Delta y^2} \right) = f_C$$



Decompose into 4 domains

57	58	59	60	61	62	63	64
49	50	51	52	53	54	55	56
41	42	43	44	45	46	47	48
33	34	35	36	37	38	39	40
25	26	27	28	29	30	31	32
17	18	19	20	21	22	23	24
9	10	11	12	13	14	15	16
1	2	3	4	5	6	7	8

4 domains: Global ID



4 domains: Local ID

PE#2

13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

PE#3

13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

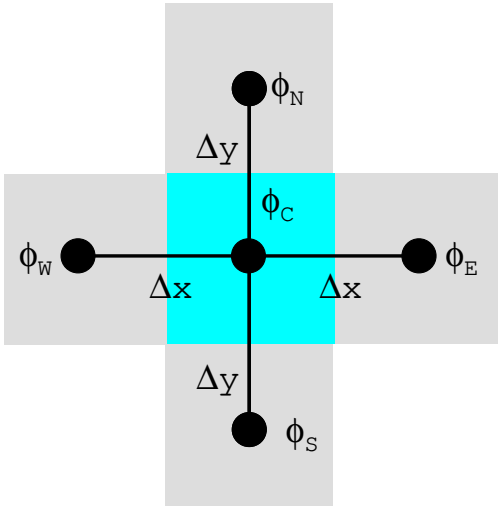
PE#0

13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

PE#1

13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

External Points: Overlapped Region



PE#2

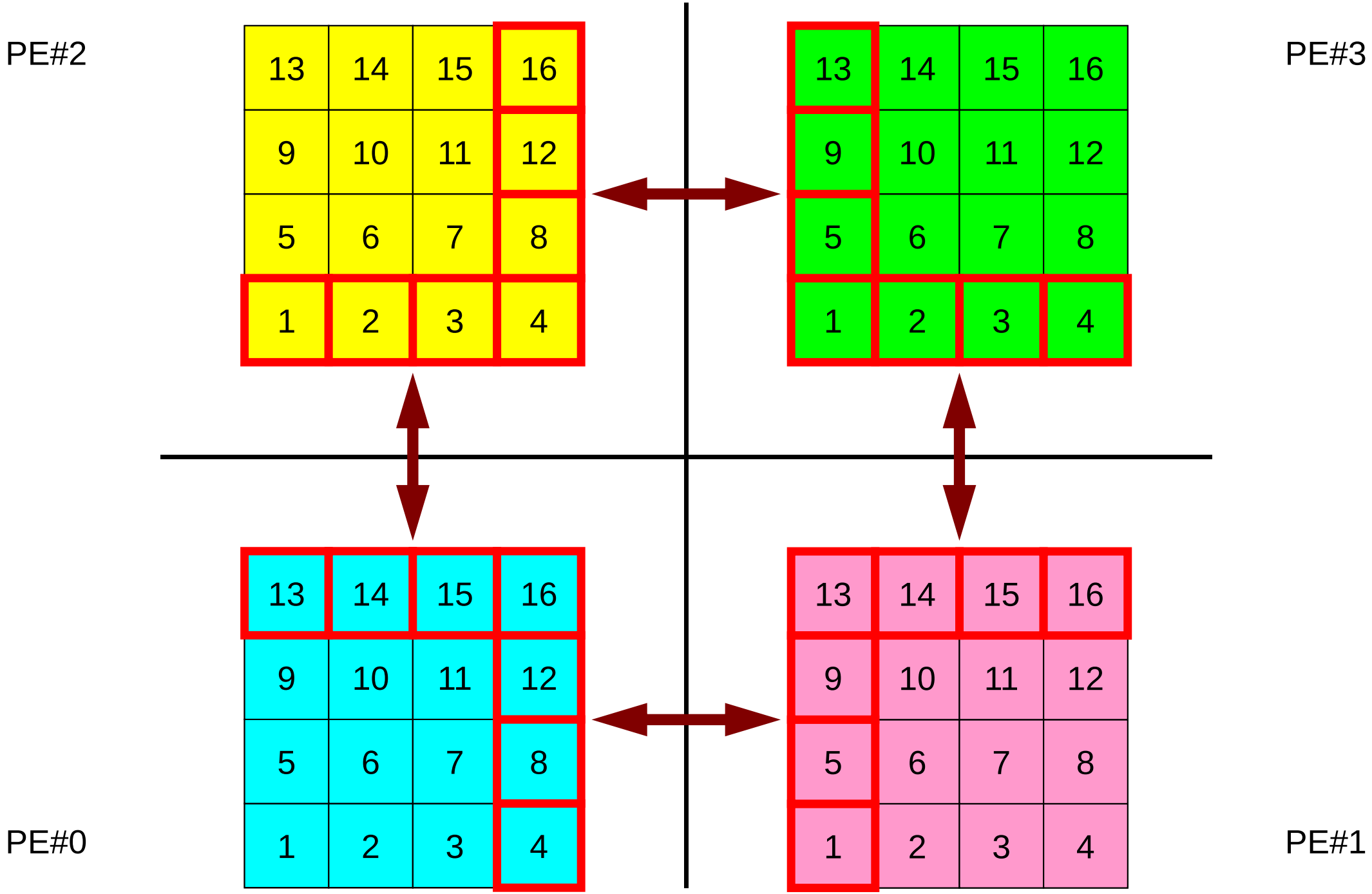
PE#3

13	14	15	16	13	14	15	16
9	10	11	12	9	10	11	12
5	6	7	8	5	6	7	8
1	2	3	4	1	2	3	4
13	14	15	16	13	14	15	16
9	10	11	12	9	10	11	12
5	6	7	8	5	6	7	8
1	2	3	4	1	2	3	4

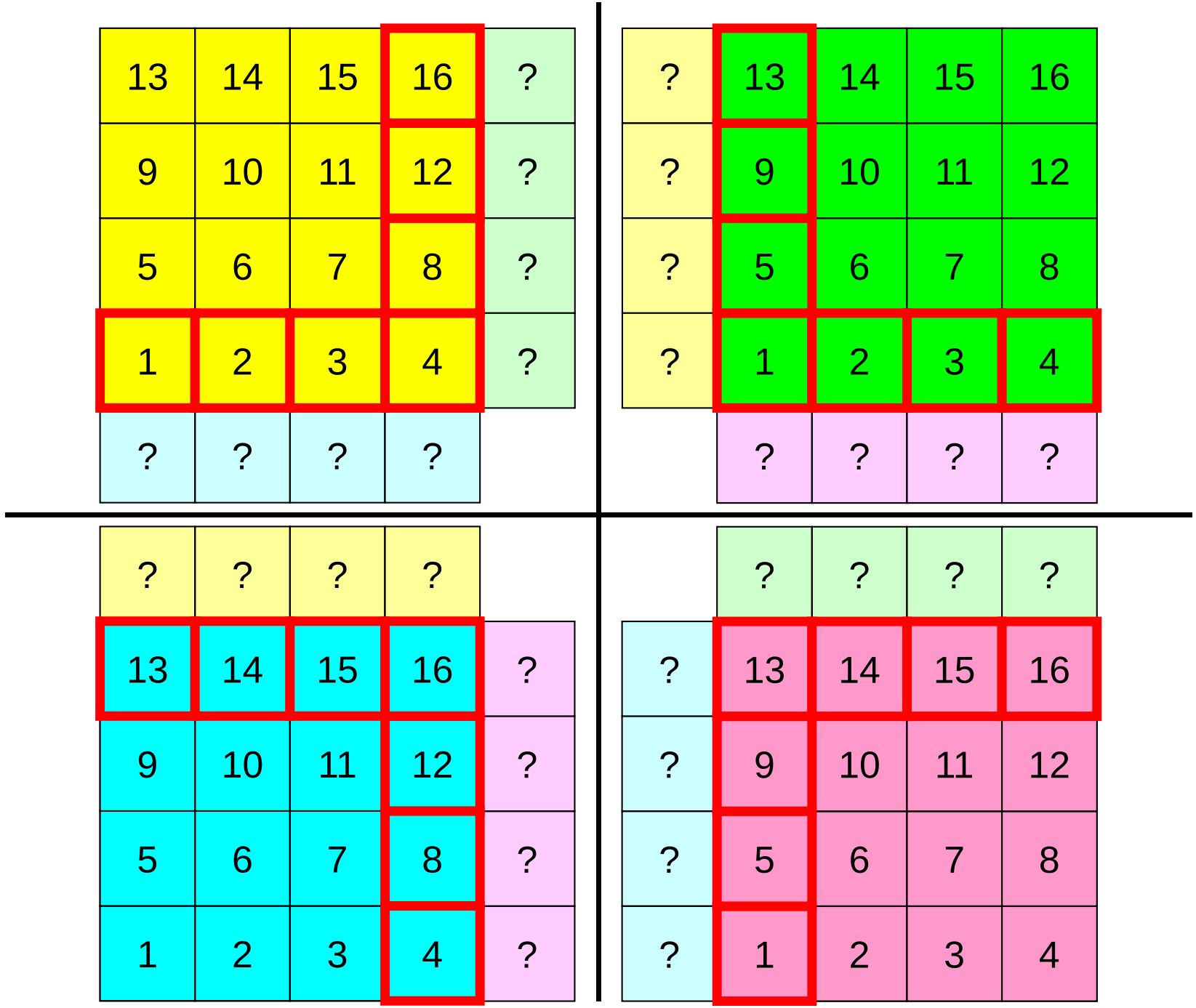
PE#0

PE#1

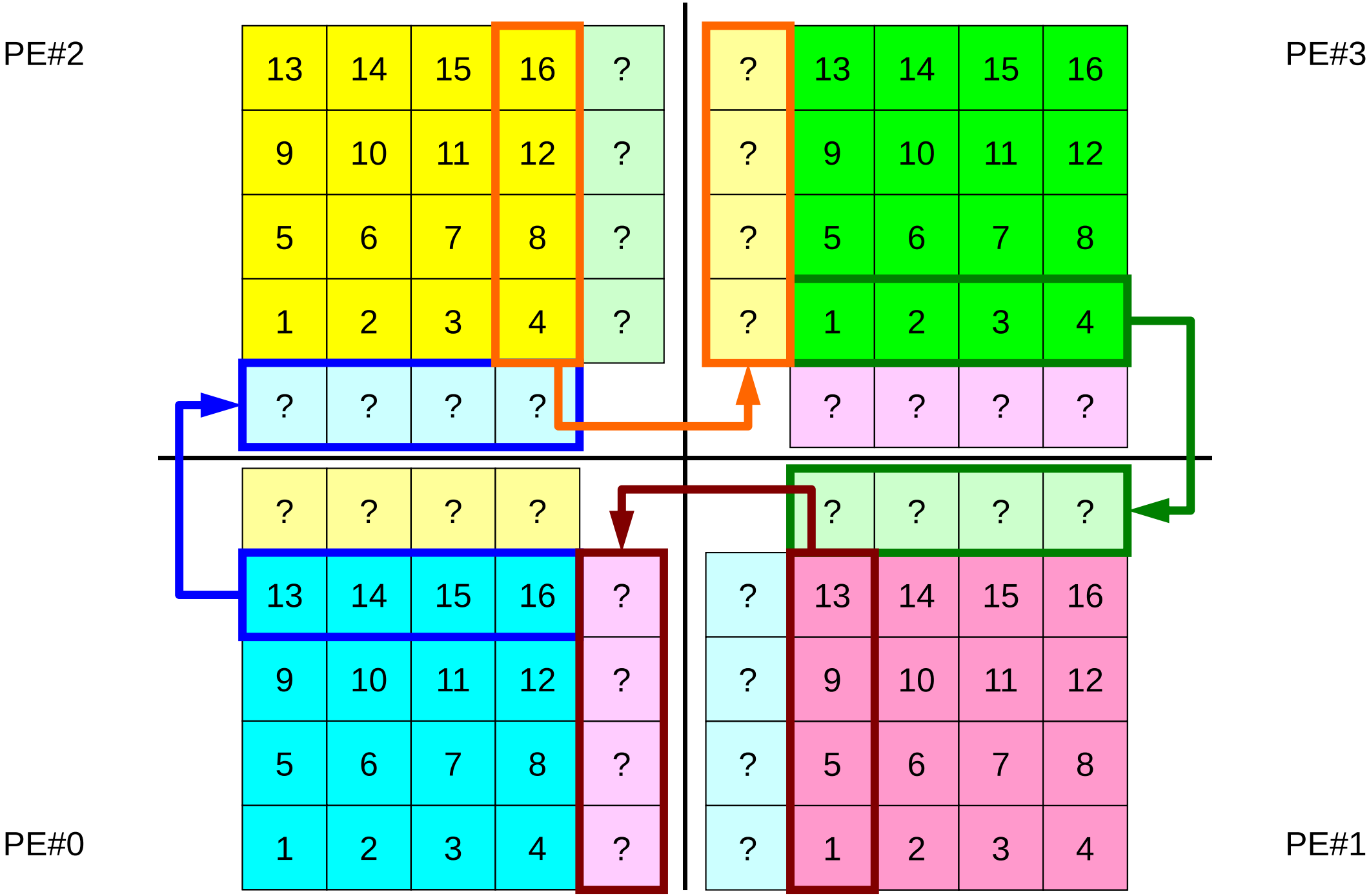
External Points: Overlapped Region



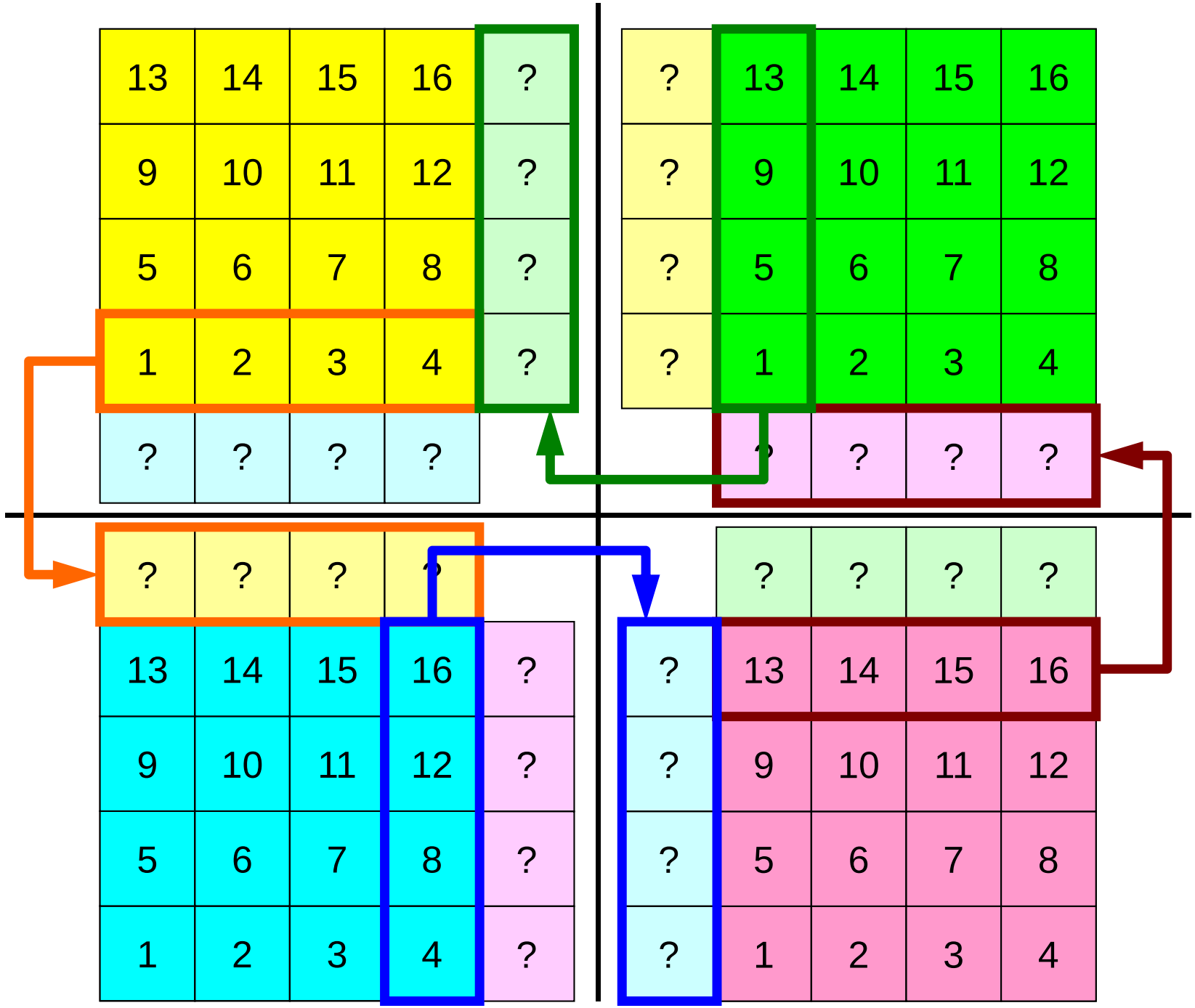
Local ID of External Points ?



Overlapped Region



Overlapped Region



Point-to-Point Communication

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  - 2D FDM
  - Problem Setting
  - Distributed Local Data and Communication Table
  - Implementation
- Report S2

Problem Setting: 2D FDM

57	58	59	60	61	62	63	64
49	50	51	52	53	54	55	56
41	42	43	44	45	46	47	48
33	34	35	36	37	38	39	40
25	26	27	28	29	30	31	32
17	18	19	20	21	22	23	24
9	10	11	12	13	14	15	16
1	2	3	4	5	6	7	8

- 2D region with 64 meshes (8x8)
- Each mesh has global ID from 1 to 64
  - In this example, this global ID is considered as dependent variable, such as temperature, pressure etc.
  - Something like computed results

Problem Setting: Distributed Local Data

PE#2

57	58	59	60
49	50	51	52
41	42	43	44
33	34	35	36

PE#3

61	62	63	64
53	54	55	56
45	46	47	48
37	38	39	40

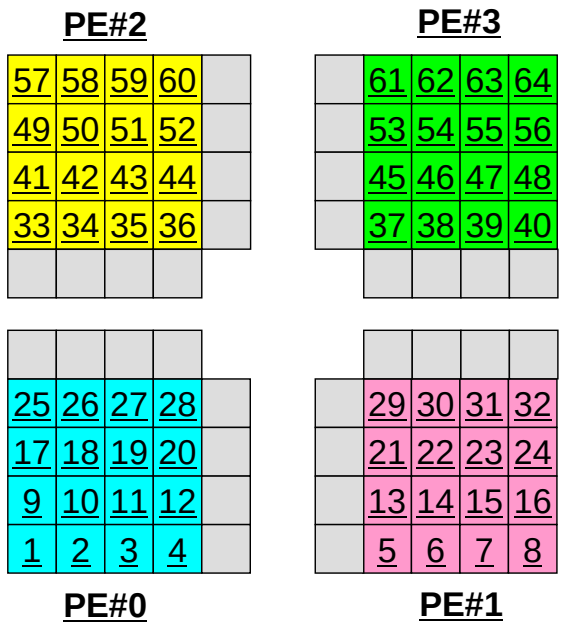
25	26	27	28
17	18	19	20
9	10	11	12
1	2	3	4

PE#0

29	30	31	32
21	22	23	24
13	14	15	16
5	6	7	8

PE#1

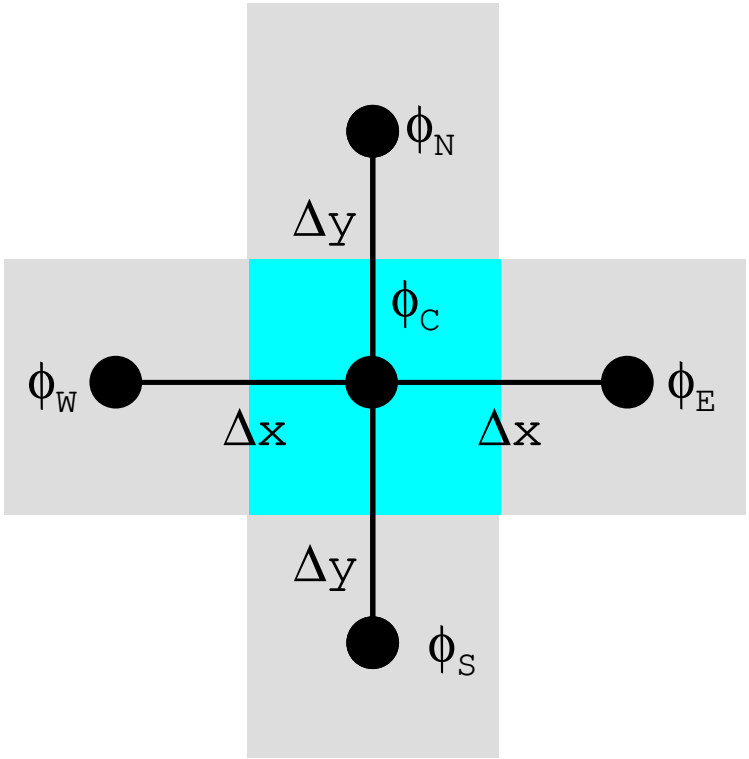
- 4 sub-domains.
- Info. of external points (global ID of mesh) is received from neighbors.
  - PE#0 receives □



Operations of 2D FDM

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = f$$

$$\left(\frac{\phi_E - 2\phi_C + \phi_W}{\Delta x^2} \right) + \left(\frac{\phi_N - 2\phi_C + \phi_S}{\Delta y^2} \right) = f_C$$

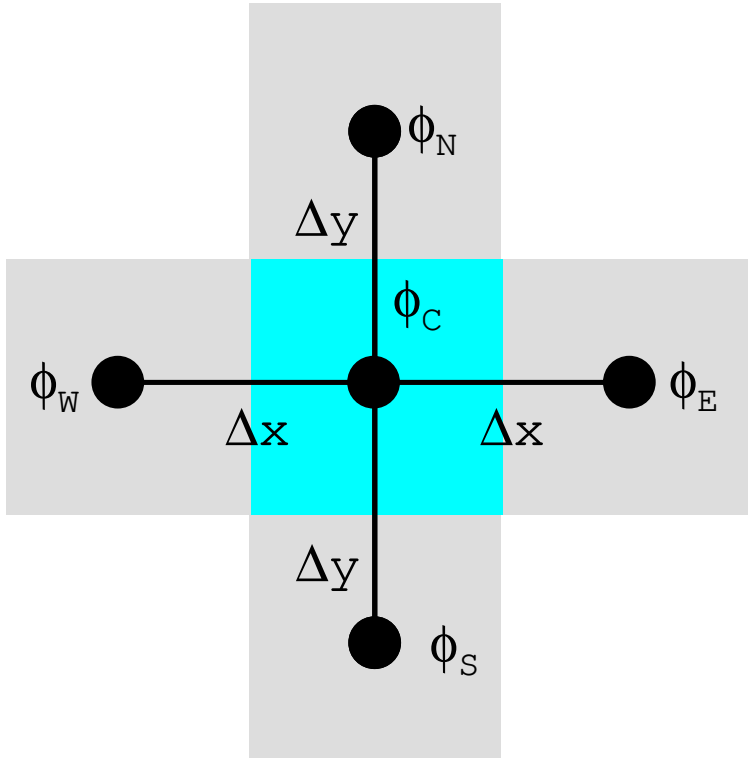


57	58	59	60	61	62	63	64
49	50	51	52	53	54	55	56
41	42	43	44	45	46	47	48
33	34	35	36	37	38	39	40
25	26	27	28	29	30	31	32
17	18	19	20	21	22	23	24
9	10	11	12	13	14	15	16
1	2	3	4	5	6	7	8

Operations of 2D FDM

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = f$$

$$\left(\frac{\phi_E - 2\phi_C + \phi_W}{\Delta x^2} \right) + \left(\frac{\phi_N - 2\phi_C + \phi_S}{\Delta y^2} \right) = f_C$$



57	58	59	60	61	62	63	64
49	50	51	52	53	54	55	56
41	42	43	44	45	46	47	48
33	34	35	36	37	38	39	40
25	26	27	28	29	30	31	32
17	18	19	20	21	22	23	24
9	10	11	12	13	14	15	16
1	2	3	4	5	6	7	8

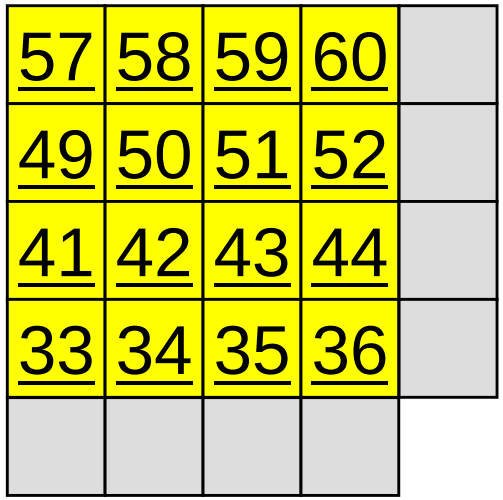
Computation (1/3)

- On each PE, info. of internal pts (i=1-N(=16)) are read from distributed local data, info. of boundary pts are sent to neighbors, and they are received as info. of external pts.

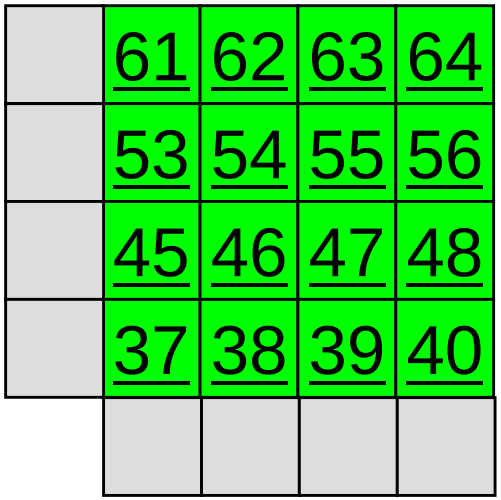
Computation (2/3): Before Send/Recv

PE#2

1: 33	9: 49	17: ?
2: 34	10: 50	18: ?
3: 35	11: 51	19: ?
4: 36	12: 52	20: ?
5: 41	13: 57	21: ?
6: 42	14: 58	22: ?
7: 43	15: 59	23: ?
8: 44	16: 60	24: ?

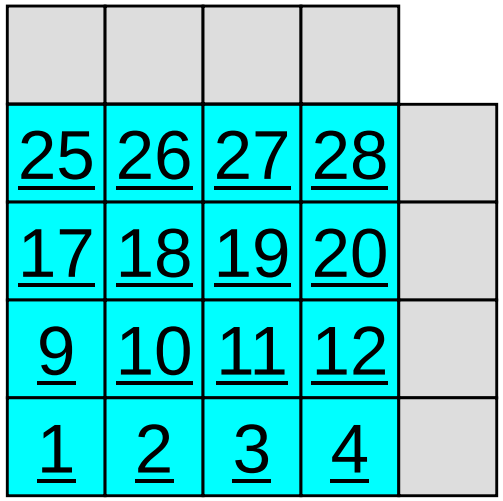


PE#3

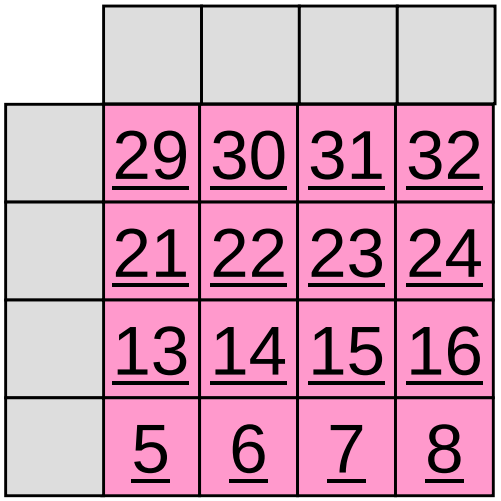


1: 37	9: 53	17: ?
2: 38	10: 54	18: ?
3: 39	11: 55	19: ?
4: 40	12: 56	20: ?
5: 45	13: 61	21: ?
6: 46	14: 62	22: ?
7: 47	15: 63	23: ?
8: 48	16: 64	24: ?

1: 1	9: 17	17: ?
2: 2	10: 18	18: ?
3: 3	11: 19	19: ?
4: 4	12: 20	20: ?
5: 9	13: 25	21: ?
6: 10	14: 26	22: ?
7: 11	15: 27	23: ?
8: 12	16: 28	24: ?



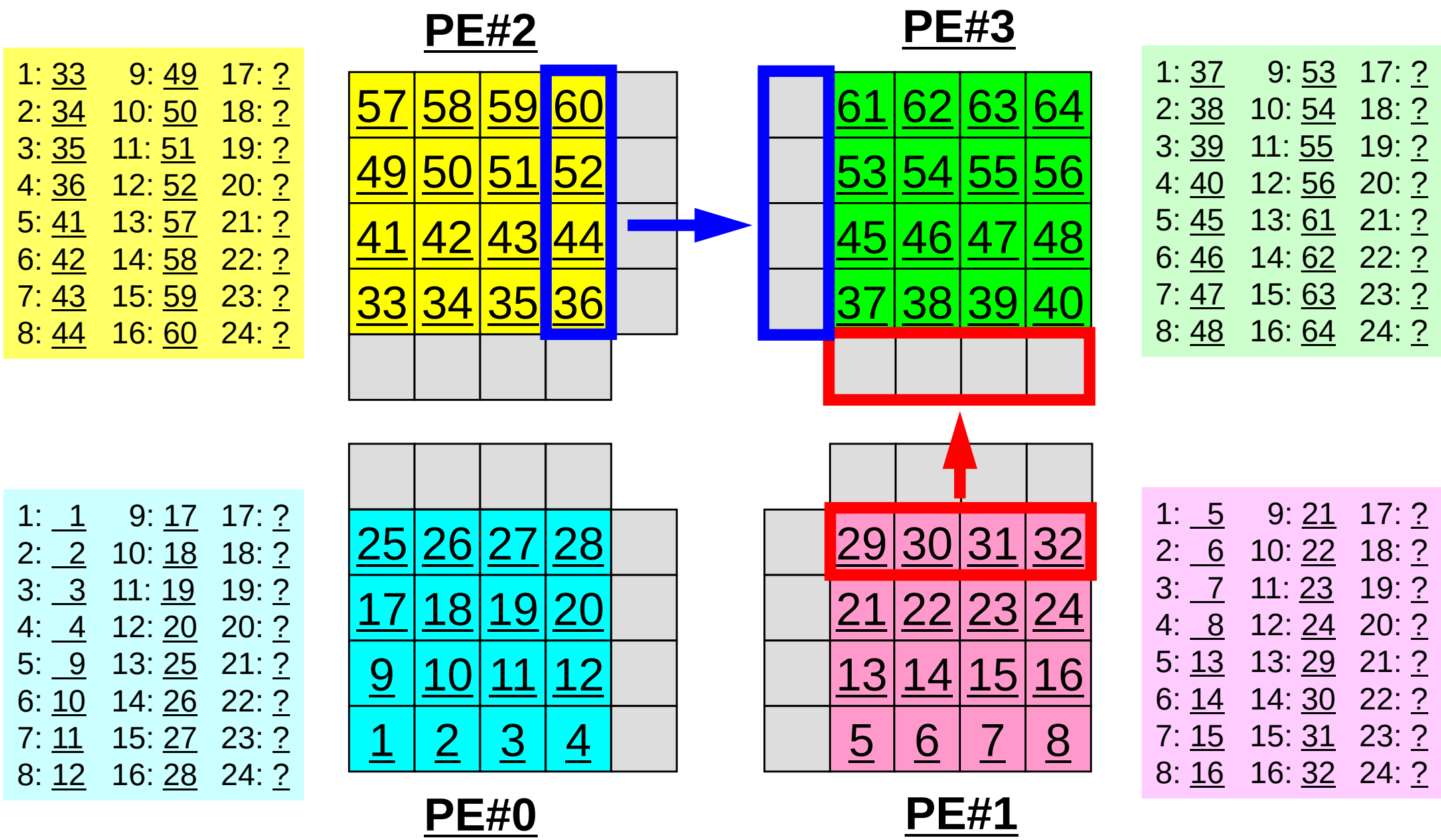
PE#0



PE#1

1: 5	9: 21	17: ?
2: 6	10: 22	18: ?
3: 7	11: 23	19: ?
4: 8	12: 24	20: ?
5: 13	13: 29	21: ?
6: 14	14: 30	22: ?
7: 15	15: 31	23: ?
8: 16	16: 32	24: ?

Computation (2/3): Before Send/Recv



Computation (3/3): After Send/Recv

PE#2

57	58	59	60	61
49	50	51	52	53
41	42	43	44	45
33	34	35	36	37
25	26	27	28	

1: 33 2: 34 3: 35 4: 36 5: 41 6: 42 7: 43 8: 44
9: 49 10: 50 11: 51 12: 52 13: 57 14: 58 15: 59 16: 60
17: 37 18: 45 19: 53 20: 61 21: 25 22: 26 23: 27 24: 28

PE#3

60	61	62	63	64
52	53	54	55	56
44	45	46	47	48
36	37	38	39	40
	29	30	31	32

1: 37 2: 38 3: 39 4: 40 5: 45 6: 46 7: 47 8: 48
9: 53 10: 54 11: 55 12: 56 13: 61 14: 62 15: 63 16: 64
17: 36 18: 44 19: 52 20: 60 21: 29 22: 30 23: 31 24: 32

33	34	35	36	
25	26	27	28	29
17	18	19	20	21
9	10	11	12	13
1	2	3	4	5

1: 1 2: 2 3: 3 4: 4 5: 9 6: 10 7: 11 8: 12
9: 17 10: 18 11: 19 12: 20 13: 25 14: 26 15: 27 16: 28
17: 5 18: 14 19: 21 20: 29 21: 33 22: 34 23: 35 24: 36

PE#0

	37	38	39	40
28	29	30	31	32
20	21	22	23	24
12	13	14	15	16
4	5	6	7	8

1: 5 2: 6 3: 7 4: 8 5: 13 6: 14 7: 15 8: 16
9: 21 10: 22 11: 23 12: 24 13: 29 14: 30 15: 31 16: 32
17: 4 18: 12 19: 20 20: 28 21: 37 22: 38 23: 39 24: 40

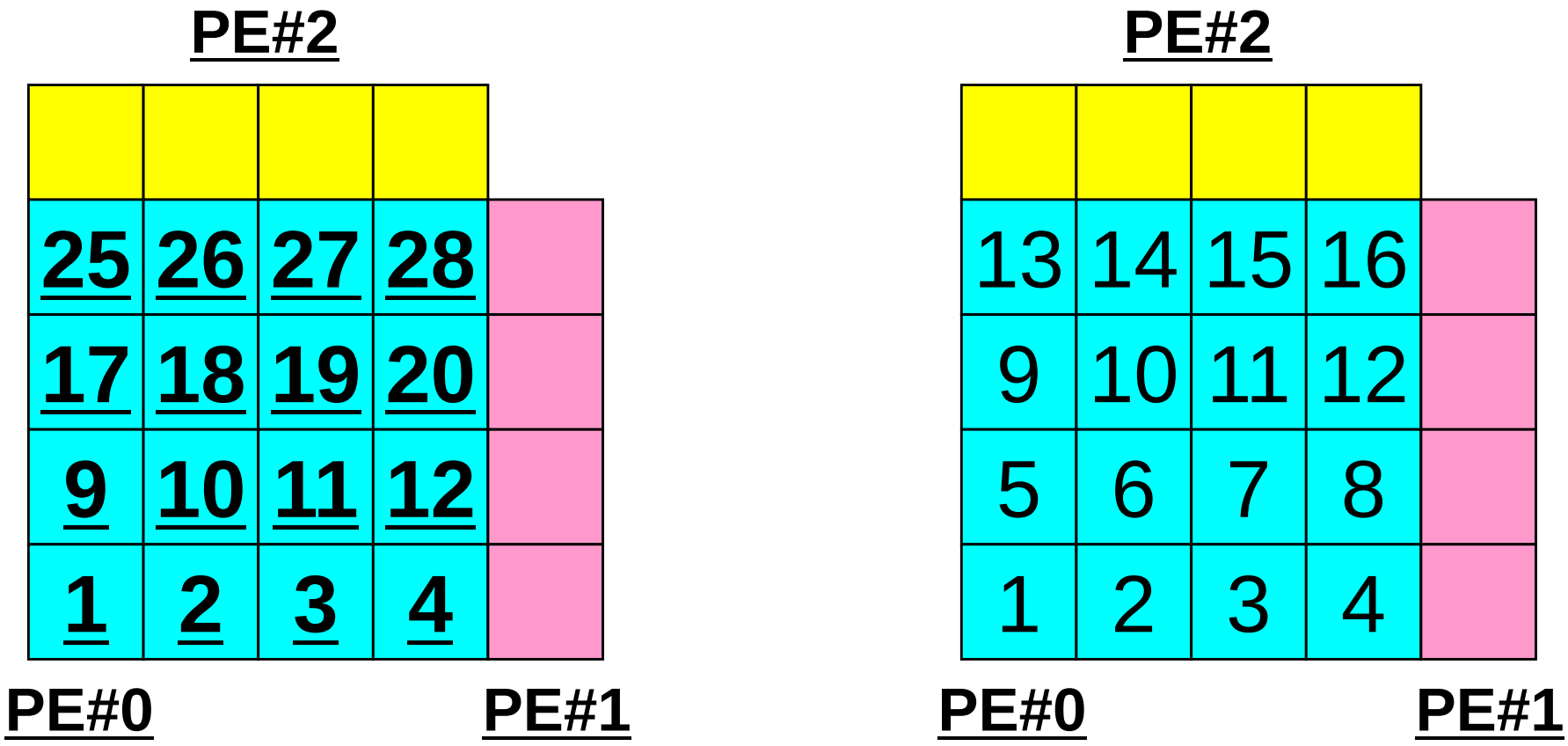
PE#1

Point-to-Point Communication

- What is PtoP Communication ?
- 2D Problem, Generalized Communication Table
  - 2D FDM
  - Problem Setting
  - Distributed Local Data and Communication Table
  - Implementation
- Report S2

Overview of Distributed Local Data

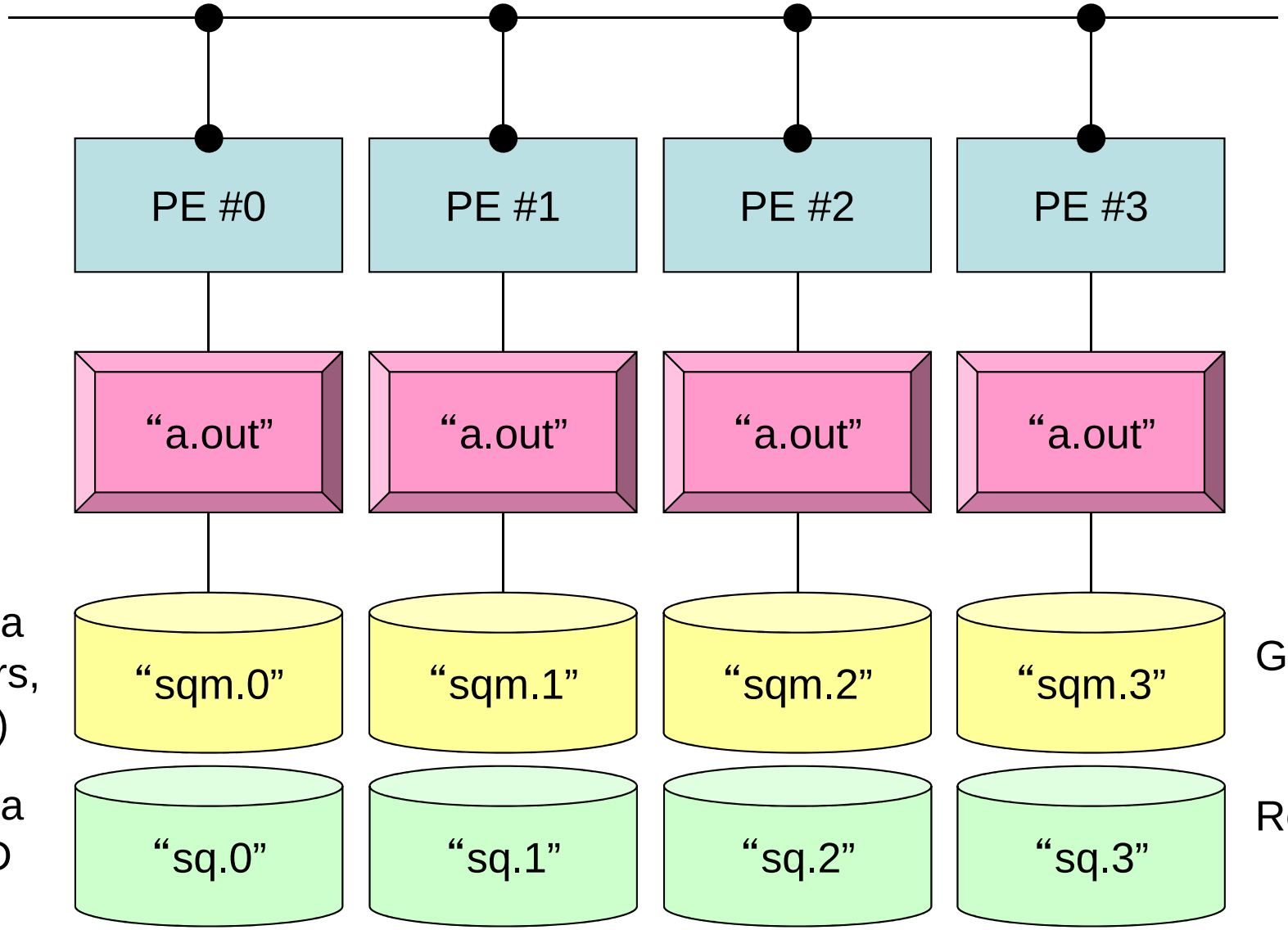
Example on PE#0



Value at each mesh (= Global ID)

Local ID

SPMD・・・



Dist. Local Data Sets (Neighbors, Comm. Tables)

Geometry

Dist. Local Data Sets (Global ID of Internal Points)

Results

2D FDM: PE#0

Information at each domain (1/4)

Internal Points

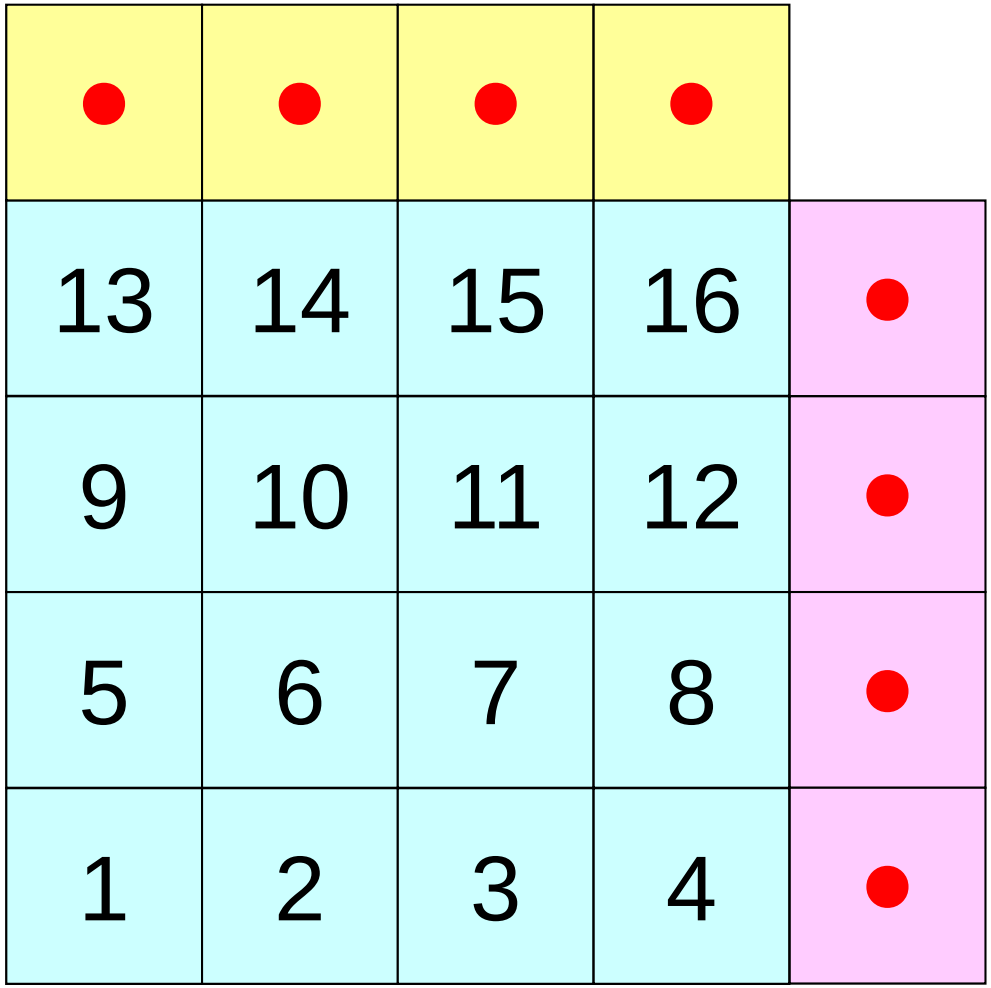
Meshes originally assigned to the domain

13	14	15	16
9	10	11	12
5	6	7	8
1	2	3	4

2D FDM: PE#0

Information at each domain (2/4)

PE#2



PE#1

Internal Points

Meshes originally assigned to the domain

External Points

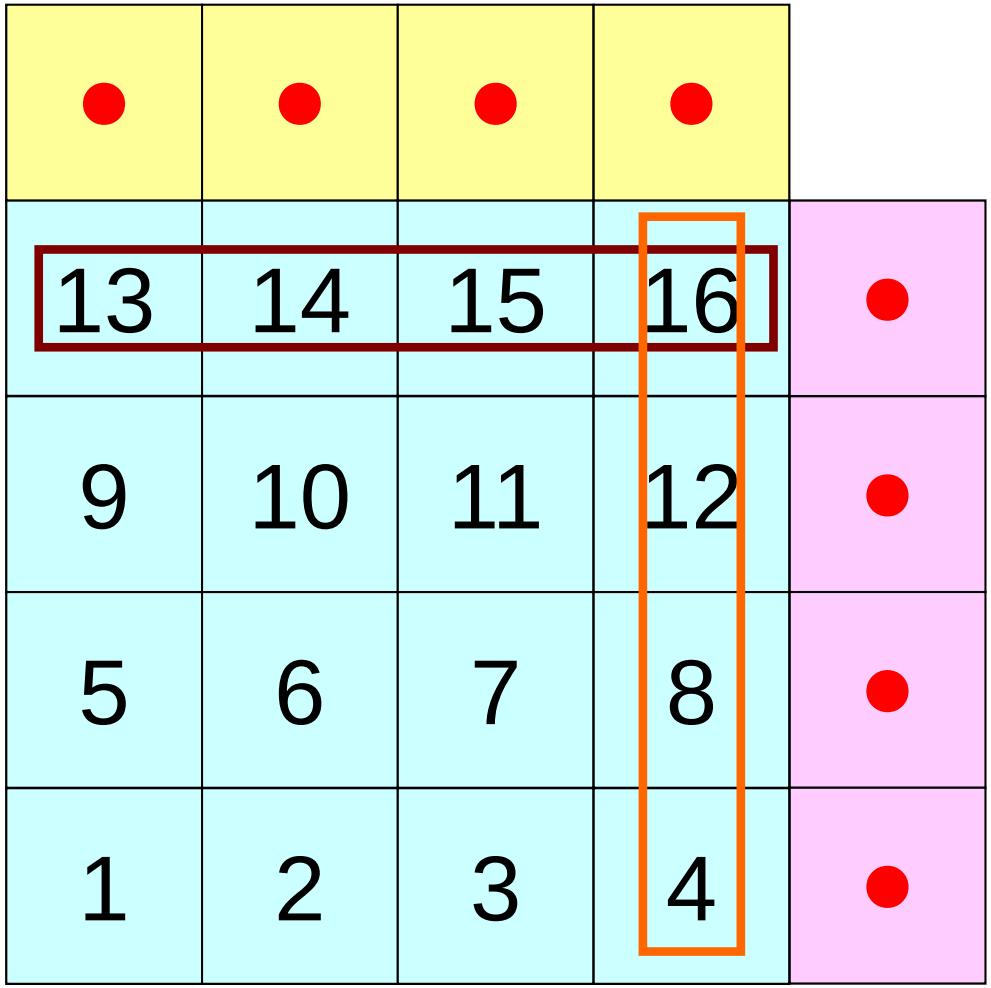
Meshes originally assigned to different domain, but required for computation of meshes in the domain (meshes in overlapped regions)

- Sleeves
- Halo

2D FDM: PE#0

Information at each domain (3/4)

PE#2



Internal Points

Meshes originally assigned to the domain

External Points

Meshes originally assigned to different domain, but required for computation of meshes in the domain (meshes in overlapped regions)

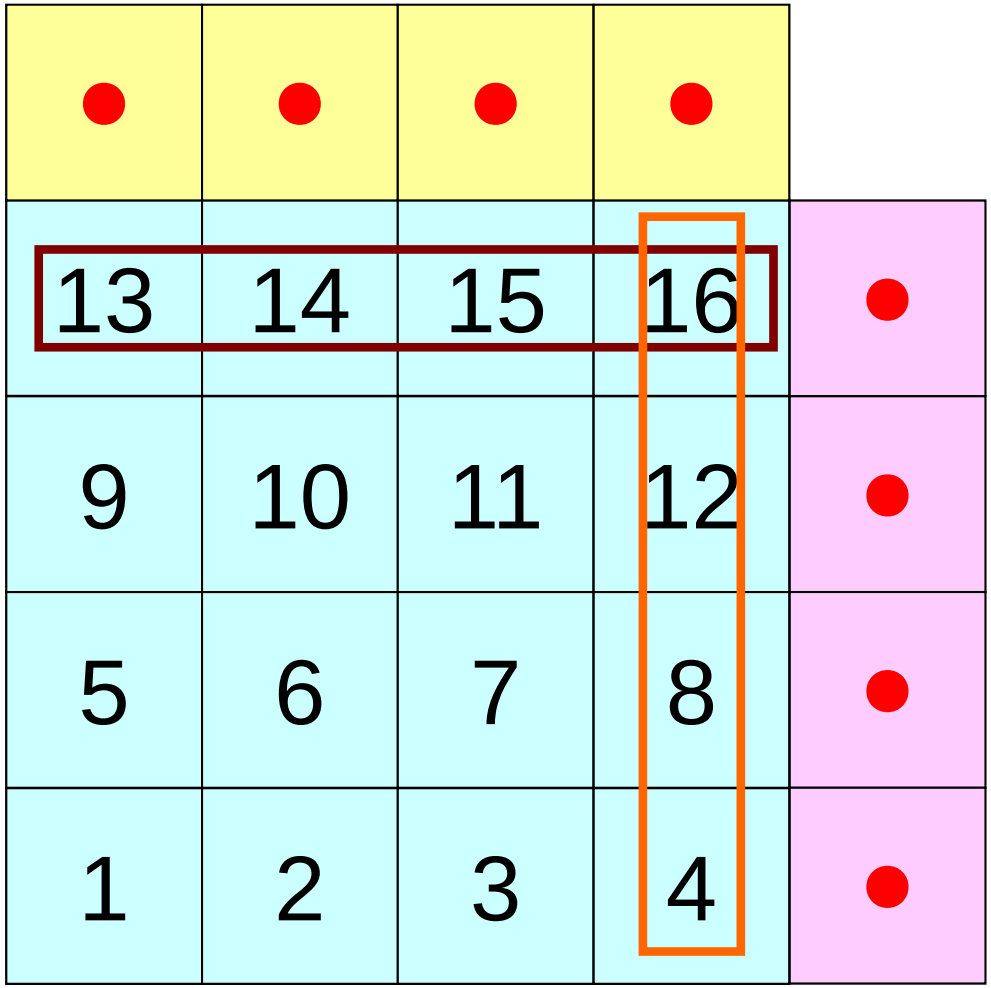
Boundary Points

Internal points, which are also external points of other domains (used in computations of meshes in other domains)

2D FDM: PE#0

Information at each domain (4/4)

PE#2



PE#1

Internal Points

Meshes originally assigned to the domain

External Points

Meshes originally assigned to different domain, but required for computation of meshes in the domain (meshes in overlapped regions)

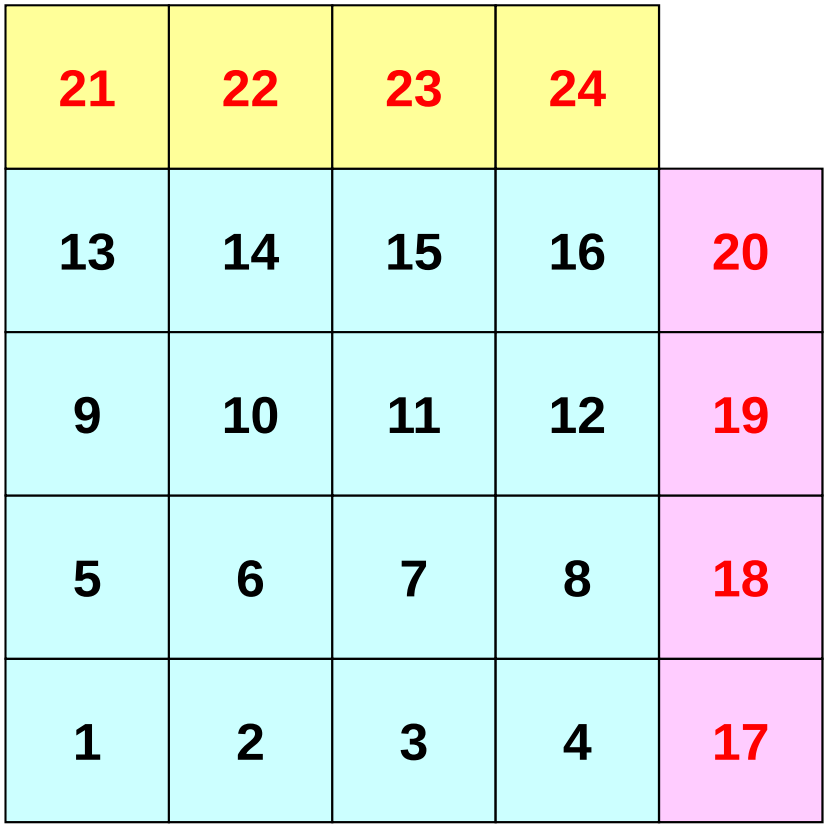
Boundary Points

Internal points, which are also external points of other domains (used in computations of meshes in other domains)

Relationships between Domains

Communication Table: External/Boundary Points Neighbors

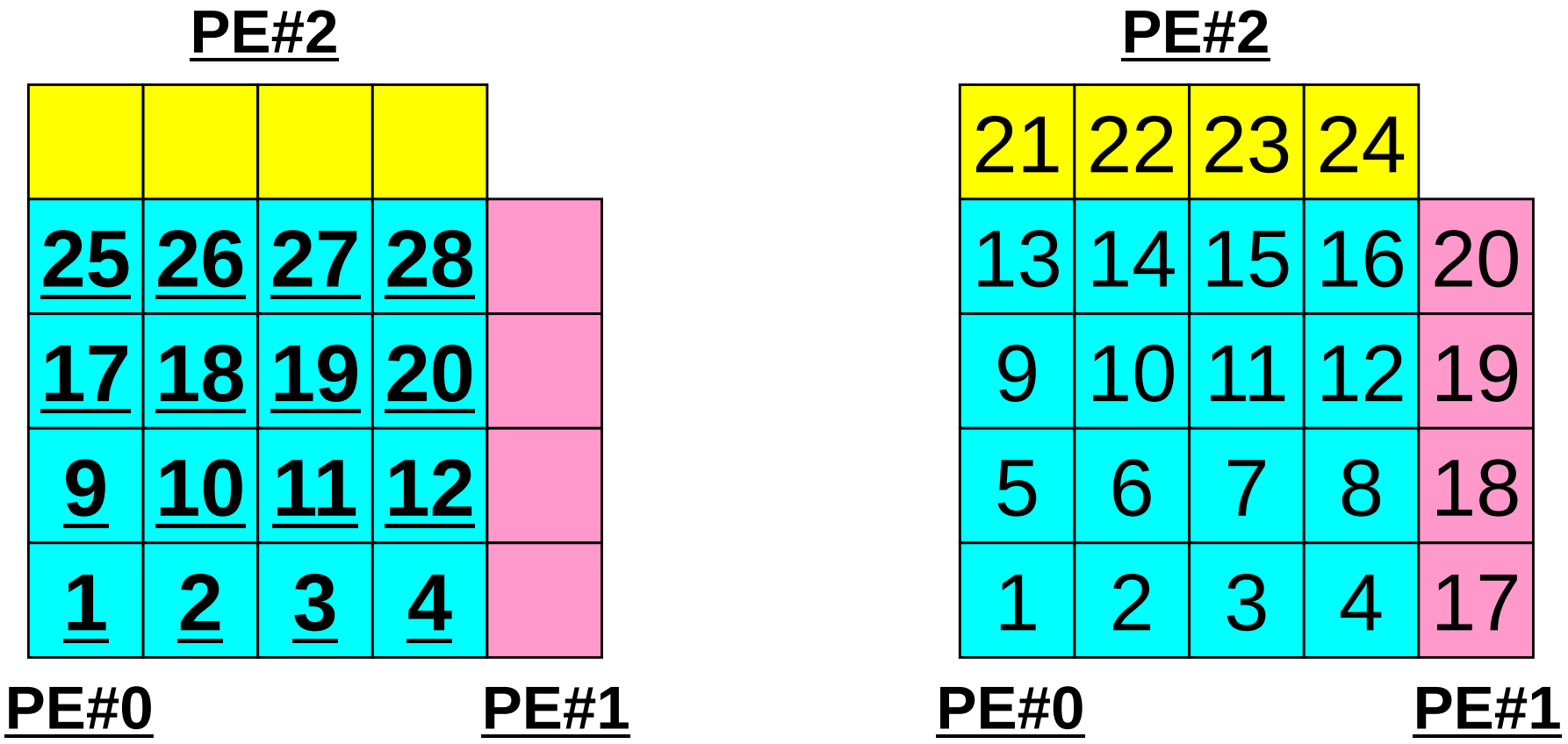
Description of Distributed Local Data



- Internal/External Points
  - Numbering: Starting from internal pts, then external pts after that
- Neighbors
  - Shares overlapped meshes
  - Number and ID of neighbors
- Import Table (Receive)
  - From where, how many, and which external points are received/imported ?
- Export Table (Send)
  - To where, how many and which boundary points are sent/exported ?

Overview of Distributed Local Data

Example on PE#0



Value at each mesh (= Global ID)

Local ID

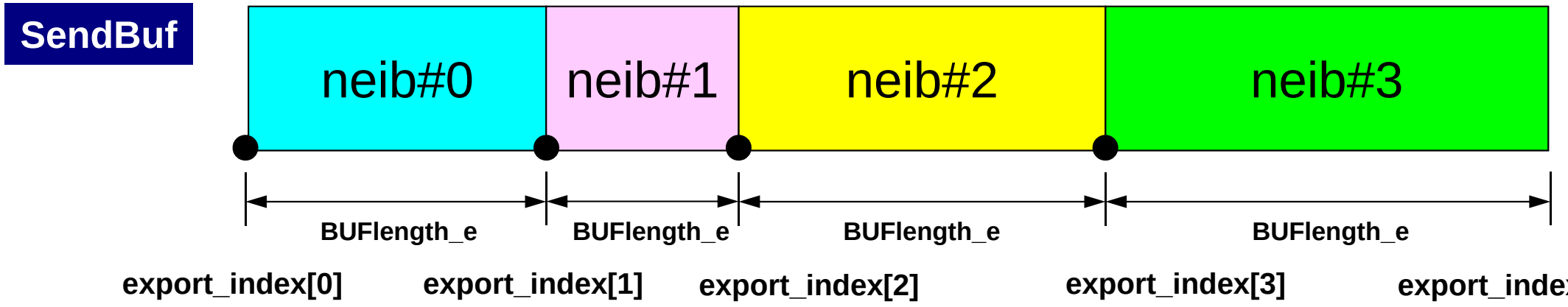
Generalized Comm. Table: Send

- Neighbors
  - NeibPETot, NeibPE[neib]
- Message size for each neighbor
  - export_index[neib], neib= 0, NeibPETot-1
- ID of **boundary** points
  - export_item[k], k= 0, export_index[NeibPETot]-1
- Messages to each neighbor
  - SendBuf[k], k= 0, export_index[NeibPETot]-1

C

SEND: MPI_Isend/Irecv/Waitall

C



export_item (export_index[neib]:export_index[neib+1]-1) are sent to neib-th neighbor

```
for (neib=0; neib<NeibPETot;neib++){
   for (k=export_index[neib];k<export_index[neib+1];k++){
      kk= export_item[k];
      SendBuf[k]= VAL[kk];
   }
}

for (neib=0; neib<NeibPETot; neib++){
  tag= 0;
  iS_e= export_index[neib];
  iE_e= export_index[neib+1];
  BUFlength_e= iE_e - iS_e

  ierr= MPI_Isend
        (&SendBuf[iS_e], BUFlength_e, MPI_DOUBLE, NeibPE[neib], 0,
         MPI_COMM_WORLD, &ReqSend[neib])
}

MPI_Waitall(NeibPETot, ReqSend, StatSend);
```

Copied to sending buffers

Generalized Comm. Table: Receive

- Neighbors
  - NeibPETot , NeibPE[neib]
- Message size for each neighbor
  - import_index[neib], neib= 0, NeibPETot-1
- ID of **external** points
  - import_item[k], k= 0, import_index[NeibPETot]-1
- Messages from each neighbor
  - RecvBuf[k], k= 0, import_index[NeibPETot]-1

C

RECV: MPI_Isend/Irecv/Waitall

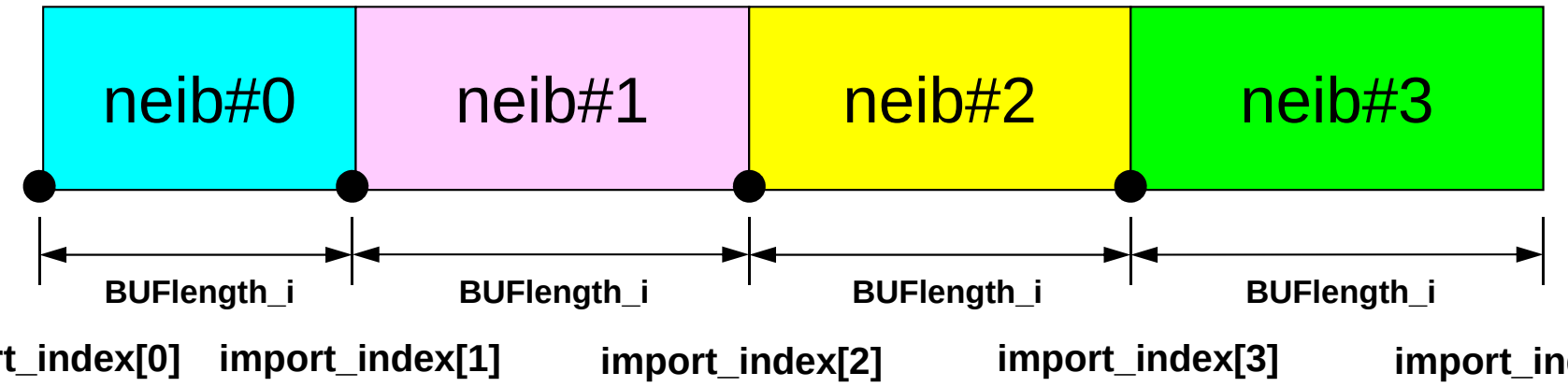
C

```
for (neib=0; neib<NeibPETot; neib++){
   tag= 0;
   iS_i= import_index[neib];
   iE_i= import_index[neib+1];
   BUFlength_i= iE_i - iS_i

   ierr= MPI_Irecv
         (&RecvBuf[iS_i], BUFlength_i, MPI_DOUBLE, NeibPE[neib], 0,
          MPI_COMM_WORLD, &ReqRecv[neib])
}

MPI_Waitall(NeibPETot, ReqRecv, StatRecv);

for (neib=0; neib<NeibPETot;neib++){
    for (k=import_index[neib];k<import_index[neib+1];k++){
       kk= import_item[k];
       VAL[kk]= RecvBuf[k];
    }
}
```

Copied from receiving buffer

import_item (import_index[neib]:import_index[neib+1]-1) are received from neib-th neighbor

RecvBuf



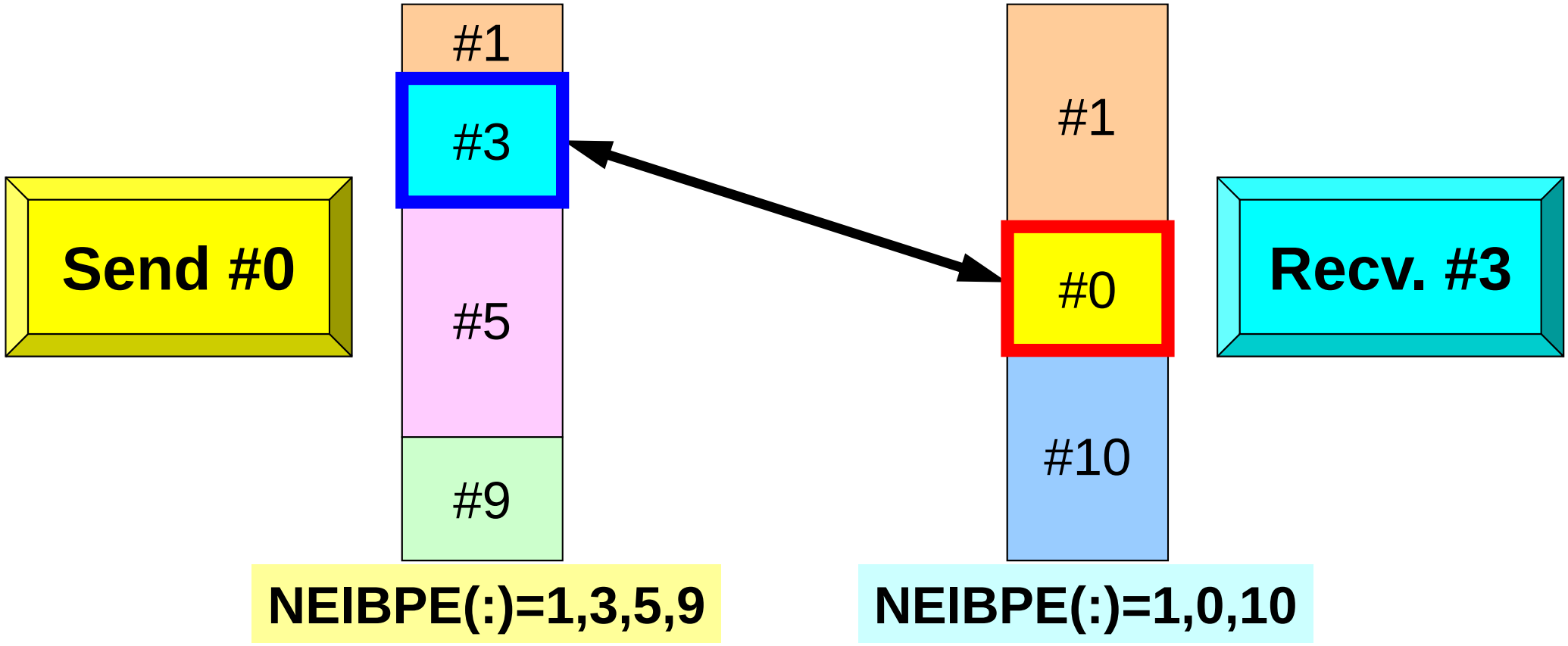
Relationship SEND/RECV

```
 do neib= 1, NEIBPETOT
   iS_e= export_index(neib-1) + 1
   iE_e= export_index(neib  )
   BUFlength_e= iE_e + 1 - iS_e

   call MPI_ISEND                                                  &
&          (SENDbuf(iS_e), BUFlength_e, MPI_INTEGER, NEIBPE(neib), 0,&
&           MPI_COMM_WORLD, request_send(neib), ierr)
  enddo
```

```
 do neib= 1, NEIBPETOT
   iS_i= import_index(neib-1) + 1
   iE_i= import_index(neib  )
   BUFlength_i= iE_i + 1 - iS_i

   call MPI_IRECV                                                  &
&          (RECVbuf(iS_i), BUFlength_i, MPI_INTEGER, NEIBPE(neib), 0,&
&           MPI_COMM_WORLD, request_recv(neib), ierr)
  enddo
```

- Consistency of ID’s of sources/destinations, size and contents of messages !
- Communication occurs when NEIBPE(neib) matches

Relationship SEND/RECV (#0 to #3)



- Consistency of ID’s of sources/destinations, size and contents of messages !
- Communication occurs when NEIBPE(neib) matches

Generalized Comm. Table (1/6)

PE#2

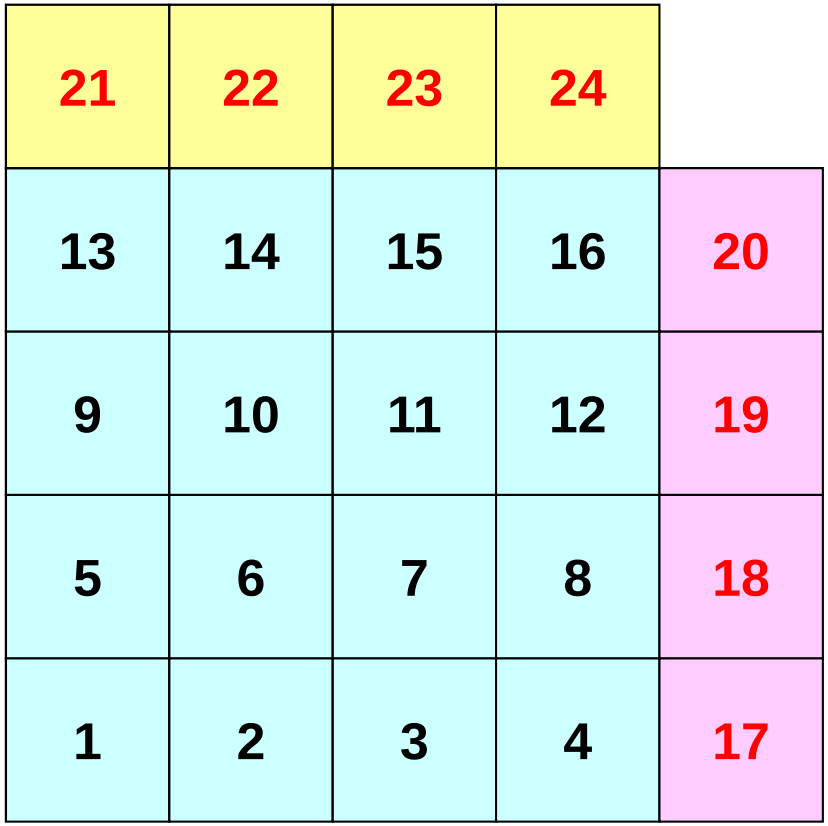
21	22	23	24	
13	14	15	16	20
9	10	11	12	19
5	6	7	8	18
1	2	3	4	17

PE#1

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORT_index
4   8
#IMPORT_items
17
18
19
20
21
22
23
24
#EXPORT_index
4   8
#EXPORT_items
4
8
12
16
13
14
15
16
```

Generalized Comm. Table (2/6)

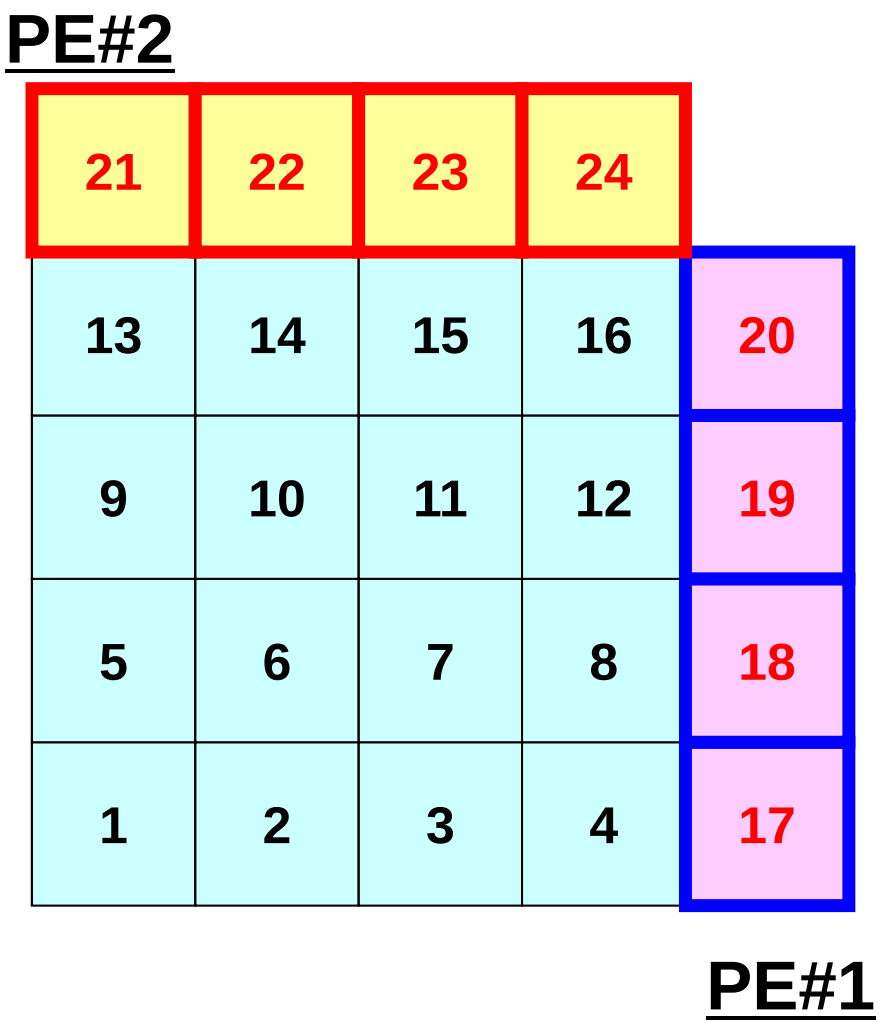
PE#2



PE#1

```
#NEIBPEtot    Number of neighbors
2
#NEIBPE       ID of neighbors
1   2
#NODE
24  16        Ext/Int Pts, Int Pts
#IMPORT_index
4   8
#IMPORT_items
17
18
19
20
21
22
23
24
#EXPORT_index
4   8
#EXPORT_items
4
8
12
16
13
14
15
16
```

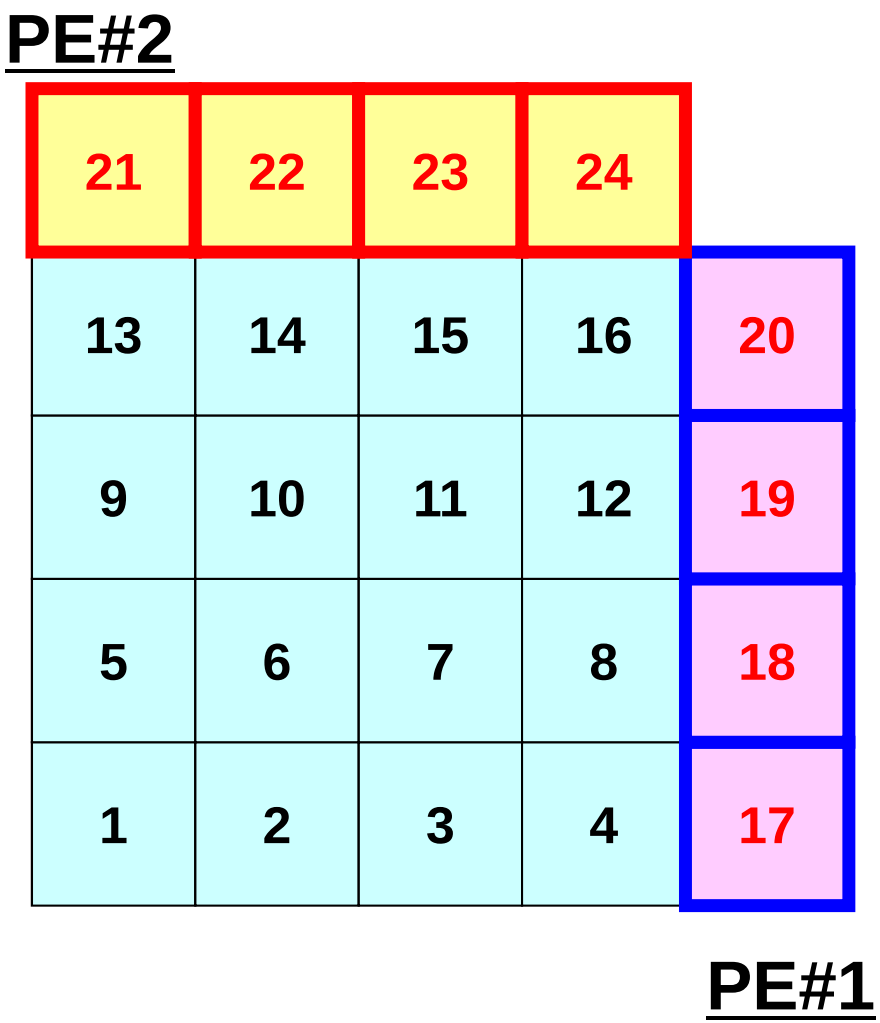
Generalized Comm. Table (3/6)




```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORT_index
4  8
#IMPORT_items
17
18
19
20
21
22
23
24
#EXPORT_index
4  8
#EXPORT_items
4
8
12
16
13
14
15
16
```

Four ext pts (1st-4th items) are imported from 1st neighbor (PE#1), and four (5th-8th items) are from 2nd neighbor (PE#2).

Generalized Comm. Table (4/6)



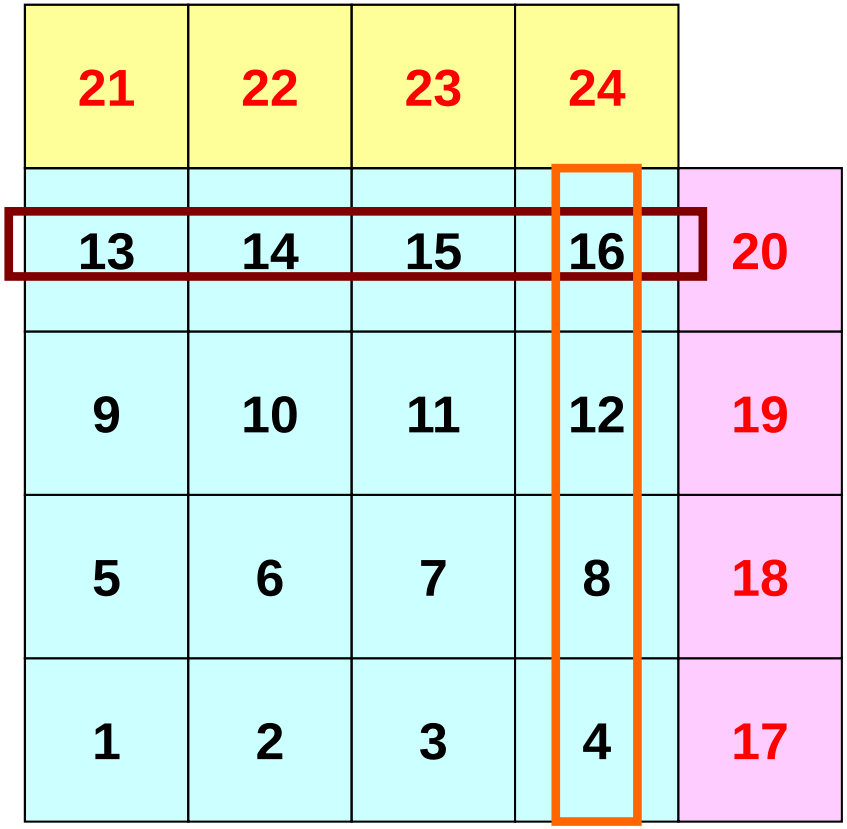

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORT_index
4   8
#IMPORT_items
17
18
19
20
21
22
23
24
#EXPORT_index
4   8
#EXPORT_items
4
8
12
16
13
14
15
16
```

imported from 1st Neighbor (PE#1) (1st-4th items)

imported from 2nd Neighbor (PE#2) (5th-8th items)

Generalized Comm. Table (5/6)

PE#2

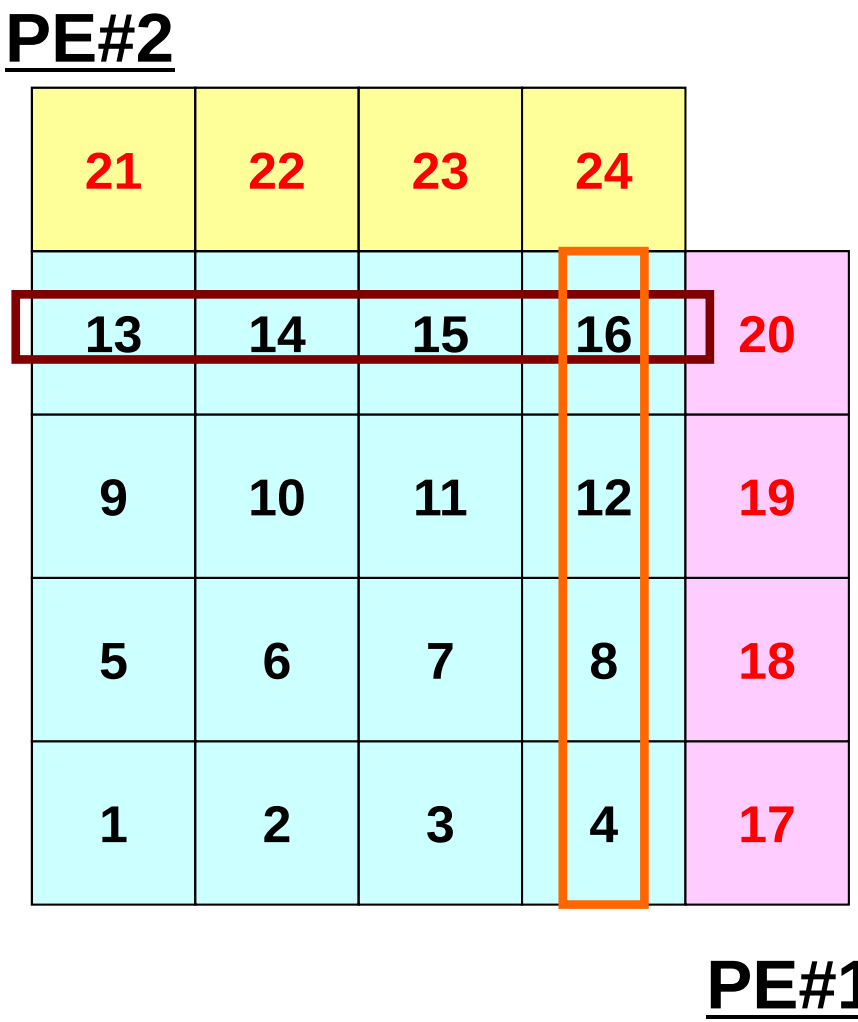


PE#1

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24  16
#IMPORT_index
4   8
#IMPORT_items
17
18
19
20
21
22
23
24
#EXPORT_index
4   8
#EXPORT_items
4
8
12
16
13
14
15
16
```

Four boundary pts (1st-4th items) are exported to 1st neighbor (PE#1), and four (5th-8th items) are to 2nd neighbor (PE#2).

Generalized Comm. Table (6/6)



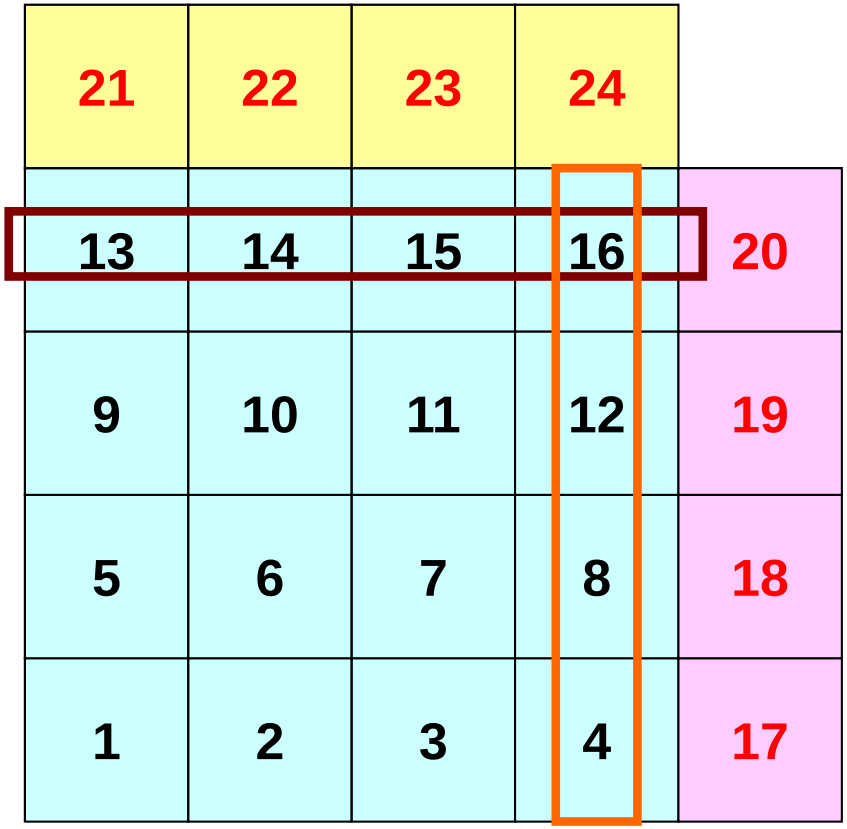

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORT_index
4   8
#IMPORT_items
17
18
19
20
21
22
23
24
#EXPORT_index
4   8
#EXPORT_items
4
8
12
16
13
14
15
16
```

exported to 1st Neighbor (PE#1) (1st-4th items)

exported to 2nd Neighbor (PE#2) (5th-8th items)

Generalized Comm. Table (6/6)

PE#2



PE#1

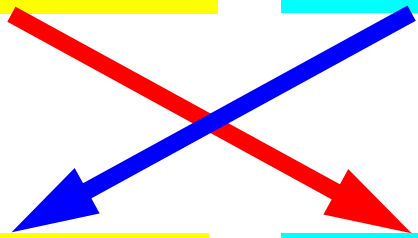
An external point is only sent from its original domain.

A boundary point could be referred from more than one domain, and sent to multiple domains (e.g. 16th mesh).

Notice: Send/Recv Arrays

```
#PE0
  send:
    VEC(start_send)~
    VEC(start_send+length_send-1)
```

```
#PE1
  send:
    VEC(start_send)~
    VEC(start_send+length_send-1)
```



```
#PE0
  recv:
    VEC(start_recv)~
    VEC(start_recv+length_recv-1)
```

```
#PE1
  recv:
    VEC(start_recv)~
    VEC(start_recv+length_recv-1)
```

- “length_send” of sending process must be equal to “length_recv” of receiving process.
  - PE#0 to PE#1, PE#1 to PE#0
- “sendbuf” and “recvbuf”: different address

Point-to-Point Communication

- What is PtoP Communication ?
- 2D Problem, Generalized Communication Table
  - 2D FDM
  - Problem Setting
  - Distributed Local Data and Communication Table
  - Implementation
- Report S2

Sample Program for 2D FDM

```
$> cd /luster/gt18/t18XXX/pFEM/mpi/S2

$ mpiifort -O3 sq-sr1.f
$ mpicc -O3 sq-sr1.c

(modify go4.sh for 4 processes)
$ qsub go4.sh
```

Example: sq-sr1.c (1/6)

C

Initialization

```
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <assert.h>
#include "mpi.h"
int main(int argc, char **argv){

        int n, np, NeibPeTot, BufLength;
        MPI_Status *StatSend, *StatRecv;
        MPI_Request *RequestSend, *RequestRecv;

        int MyRank, PeTot;
        int *val, *SendBuf, *RecvBuf, *NeibPe;
        int *ImportIndex, *ExportIndex, *ImportItem, *ExportItem;

        char FileName[80], line[80];
        int i, nn, neib;
        int iStart, iEnd;
        FILE *fp;

/*
!C +-----------+
!C | INIT. MPI |
!C +-----------+
!C===*/
        MPI_Init(&argc, &argv);
        MPI_Comm_size(MPI_COMM_WORLD, &PeTot);
        MPI_Comm_rank(MPI_COMM_WORLD, &MyRank);
```

Example: sq-sr1.c (2/6)

C

Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        ImportIndex = calloc(1+NeibPeTot, sizeof(int));
        ExportIndex = calloc(1+NeibPeTot, sizeof(int));

        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]--;}

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

Example: sq-sr1.c (2/6)

C

Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        ImportIndex = calloc(1+NeibPeTot, sizeof(int));
        ExportIndex = calloc(1+NeibPeTot, sizeof(int));

        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]-

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```

Example: sq-sr1.c (2/6)

C

Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]-

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

np Number of all meshes (internal + external)

n Number of internal meshes

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```

Example: sq-sr1.c (2/6)

C

Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        ImportIndex = calloc(1+NeibPeTot, sizeof(int));
        ExportIndex = calloc(1+NeibPeTot, sizeof(int));

        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]-

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```

Example: sq-sr1.c (2/6)

C

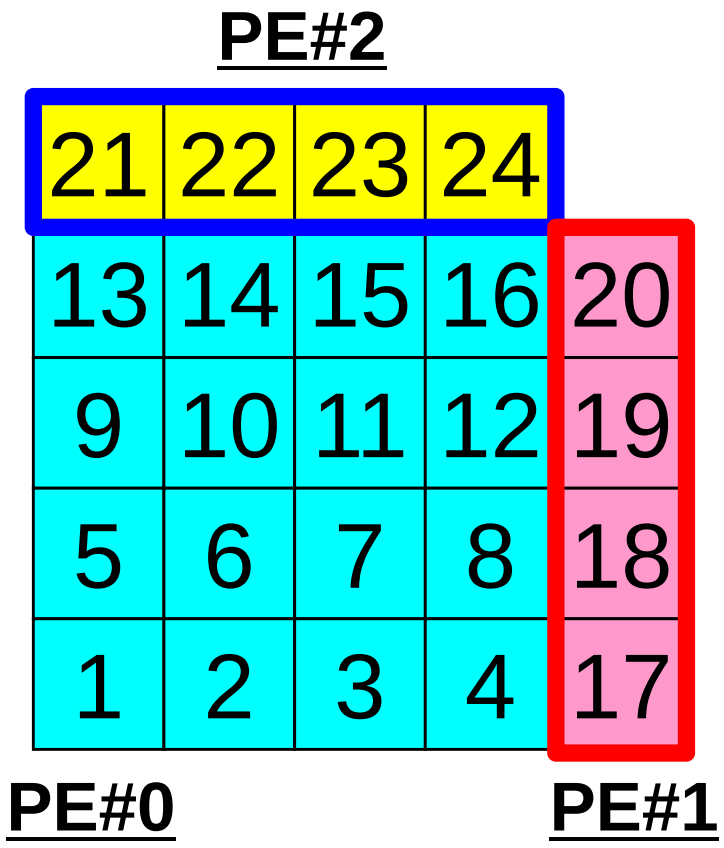
Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        ImportIndex = calloc(1+NeibPeTot, sizeof(int));
        ExportIndex = calloc(1+NeibPeTot, sizeof(int));

        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]-

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```

RECV/Import: PE#0

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```



Example: sq-sr1.c (2/6)

C

Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        ImportIndex = calloc(1+NeibPeTot, sizeof(int));
        ExportIndex = calloc(1+NeibPeTot, sizeof(int));

        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]-

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```

Example: sq-sr1.c (2/6)

C

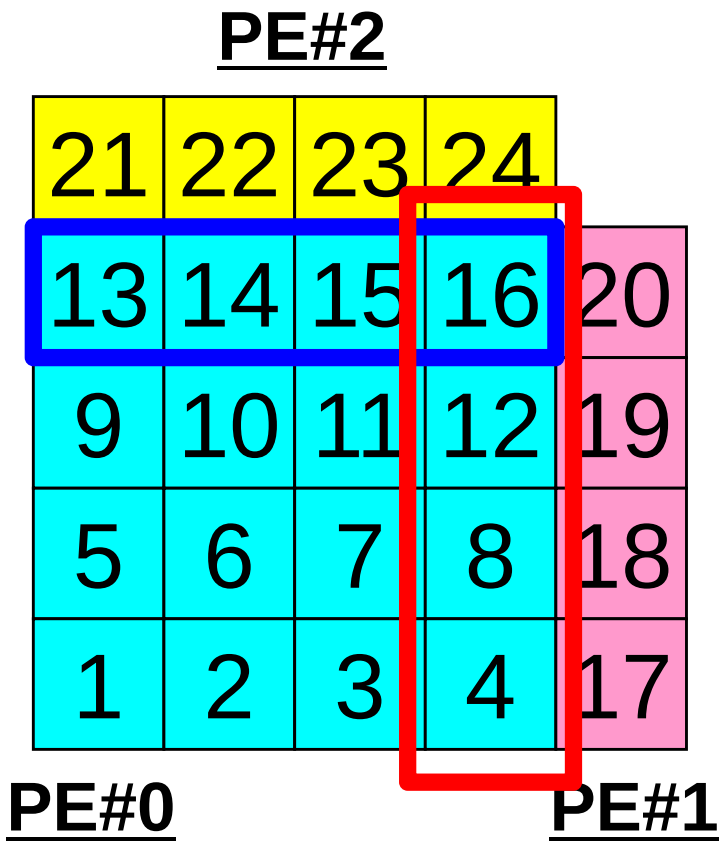
Reading distributed local data files (sqm.*)

```
/*
!C +-----------+
!C | DATA file |
!C +-----------+
!C===*/
        sprintf(FileName, "sqm.%d", MyRank);
        fp = fopen(FileName, "r");

        fscanf(fp, "%d", &NeibPeTot);
        NeibPe = calloc(NeibPeTot, sizeof(int));
        ImportIndex = calloc(1+NeibPeTot, sizeof(int));
        ExportIndex = calloc(1+NeibPeTot, sizeof(int));

        for(neib=0;neib<NeibPeTot;neib++){
                fscanf(fp, "%d", &NeibPe[neib]);
        }
        fscanf(fp, "%d %d", &np, &n);

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ImportIndex[neib]);}
        nn = ImportIndex[NeibPeTot];
        ImportItem = malloc(nn * sizeof(int));
        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ImportItem[i]); ImportItem[i]-

        for(neib=1;neib<NeibPeTot+1;neib++){
                fscanf(fp, "%d", &ExportIndex[neib]);}
        nn = ExportIndex[NeibPeTot];
        ExportItem = malloc(nn * sizeof(int));

        for(i=0;i<nn;i++){
                fscanf(fp, "%d", &ExportItem[i]);ExportItem[i]--;}
```

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```

SEND/Export: PE#0

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```



Example: sq-sr1.c (3/6)

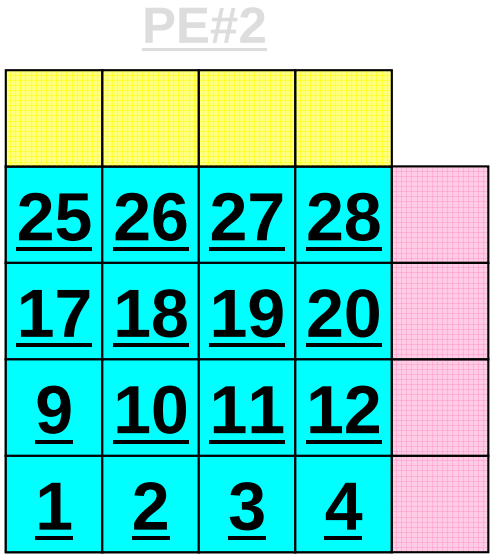
C

Reading distributed local data files (sq.*)

```
sprintf(FileName, "sq.%d", MyRank);

fp = fopen(FileName, "r");
assert(fp != NULL);

val = calloc(np, sizeof(*val));
for(i=0;i<n;i++){
        fscanf(fp, "%d", &val[i]);
}
```

n : Number of internal points
val : Global ID of meshes

val on external points are unknown at this stage.




```
1
2
3
4
9
10
11
12
17
18
19
20
25
26
27
28
```

Example: sq-sr1.c (4/6)

C

Preparation of sending/receiving buffers

```
/*
!C
!C +--------+
!C | BUFFER |
!C +--------+
!C===*/
        SendBuf = calloc(ExportIndex[NeibPeTot], sizeof(*SendBuf));
        RecvBuf = calloc(ImportIndex[NeibPeTot], sizeof(*RecvBuf));

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ExportIndex[neib];
                iEnd   = ExportIndex[neib+1];
                for(i=iStart;i<iEnd;i++){
                        SendBuf[i] = val[ExportItem[i]];
                }
        }
```

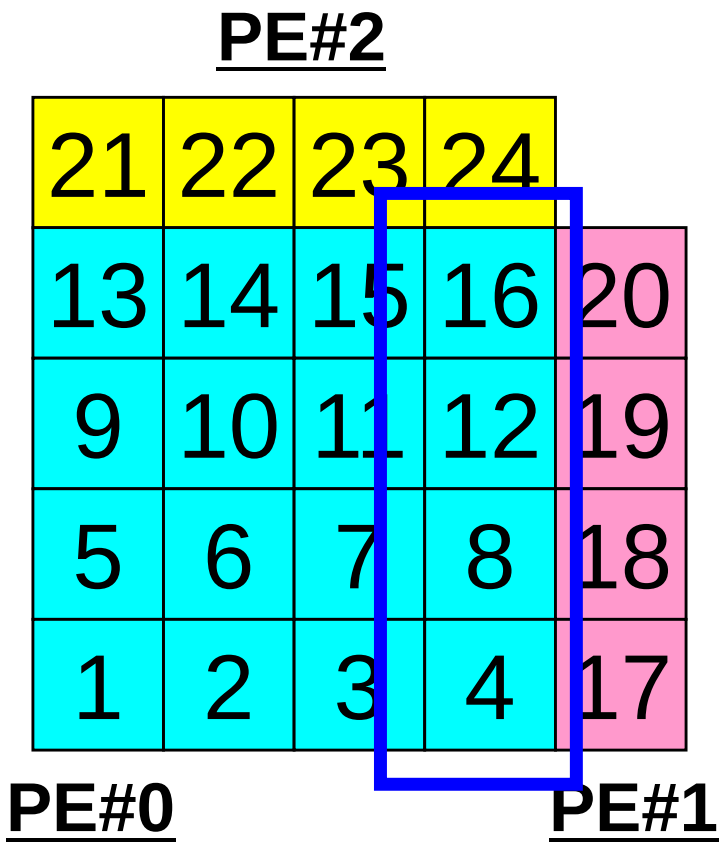
Info. of boundary points is written into sending buffer (**SendBuf**).

Info. sent to **NeibPe[neib]** is stored in **SendBuf[ExportIndex[neib]:ExportInedx[neib+1]-1]**

Sending Buffer is nice ...

C

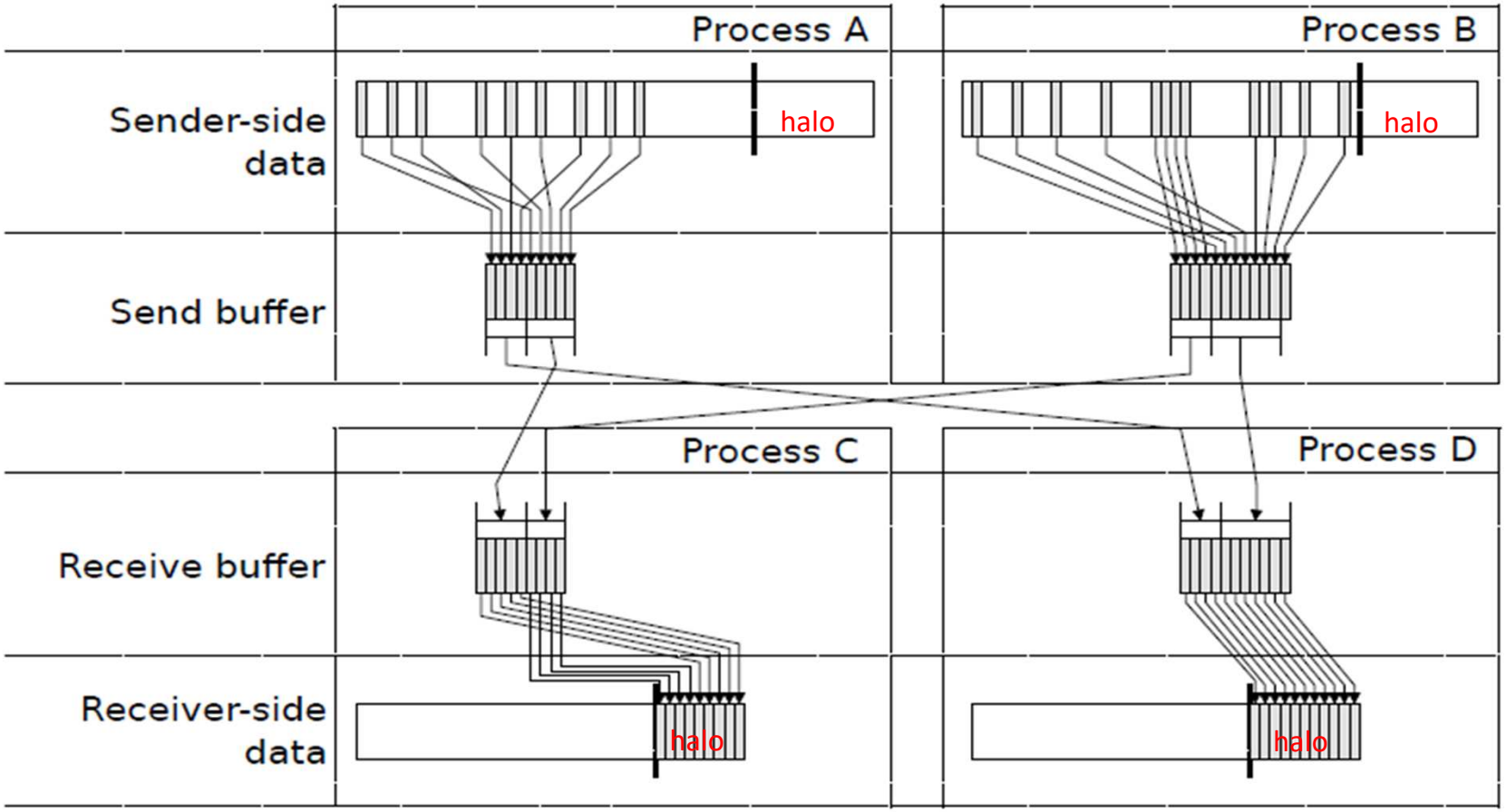
```
for (neib=0; neib<NeibPETot; neib++){
   tag= 0;
   iS_e= export_index[neib];
   iE_e= export_index[neib+1];
   BUFlength_e= iE_e - iS_e

   ierr= MPI_Isend
         (&SendBuf[iS_e], BUFlength_e, MPI_DOUBLE, NeibPE[neib], 0,
          MPI_COMM_WORLD, &ReqSend[neib])
 }
```



Numbering of these boundary nodes is not continuous, therefore the following procedure of MPI_Isend is not applied directly:

- Starting address of sending buffer
- XX-messages from that address

Communication Pattern using 1D Structure



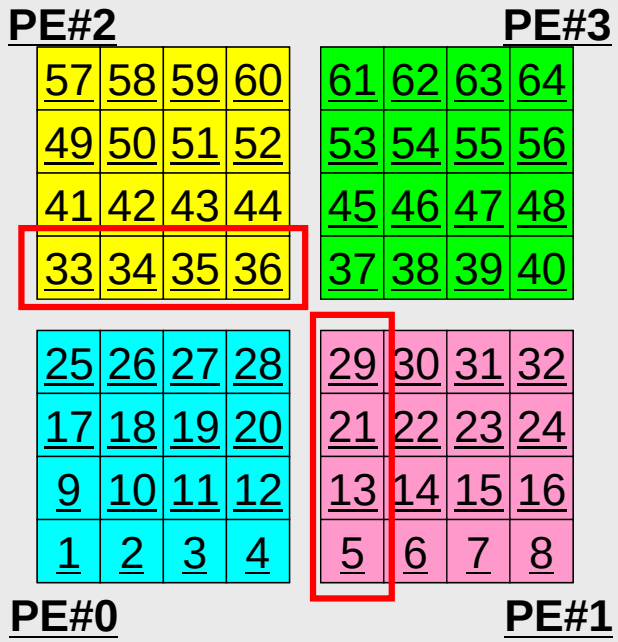
Dr. Osni Marques
（Lawrence Berkeley National Laboratory）

Example: sq-sr1.c (5/6)

C

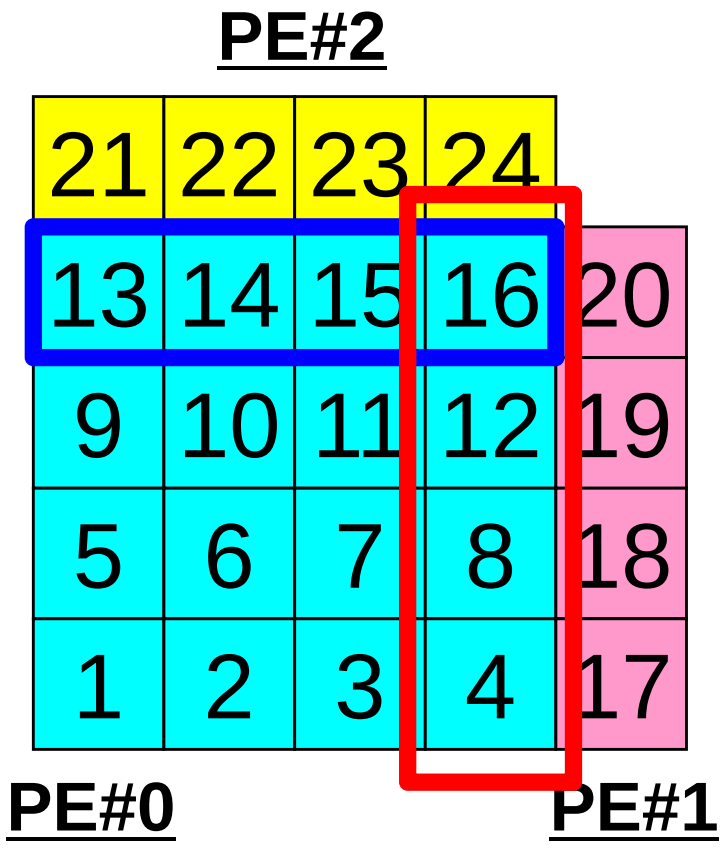
SEND/Export: MPI_Isend

```
/*
!C
!C +-----------+
!C | SEND-RECV |
!C +-----------+
!C===*/
        StatSend = malloc(sizeof(MPI_Status) * NeibPeTot);
        StatRecv = malloc(sizeof(MPI_Status) * NeibPeTot);
        RequestSend = malloc(sizeof(MPI_Request) * NeibPeTot);
        RequestRecv = malloc(sizeof(MPI_Request) * NeibPeTot);

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ExportIndex[neib];
                iEnd   = ExportIndex[neib+1];
                BufLength = iEnd - iStart;
                MPI_Isend(&SendBuf[iStart], BufLength, MPI_INT,
                                NeibPe[neib], 0, MPI_COMM_WORLD, &RequestSend[neib]);
        }

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ImportIndex[neib];
                iEnd   = ImportIndex[neib+1];
                BufLength = iEnd - iStart;

                MPI_Irecv(&RecvBuf[iStart], BufLength, MPI_INT,
                                NeibPe[neib], 0, MPI_COMM_WORLD, &RequestRecv[neib]);
        }
```



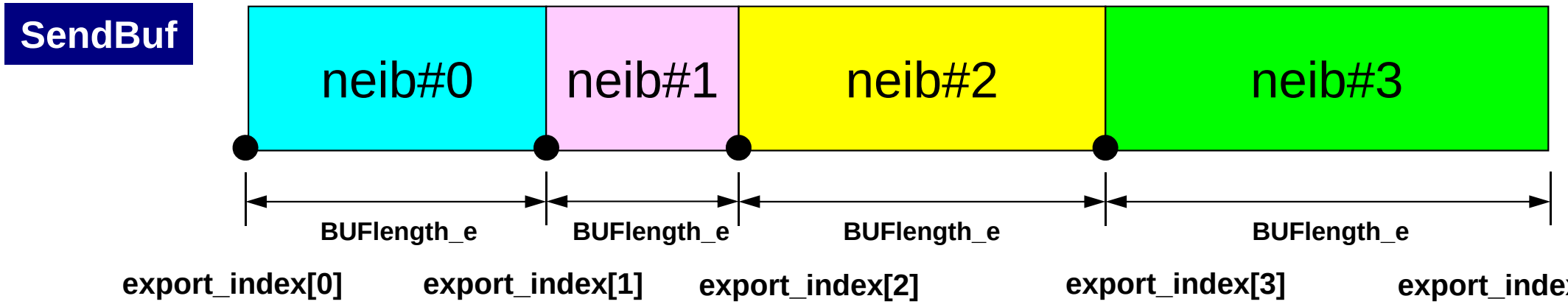
SEND/Export: PE#0

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```



SEND: MPI_Isend/Irecv/Waitall

C



export_item (export_index[neib]:export_index[neib+1]-1) are sent to neib-th neighbor

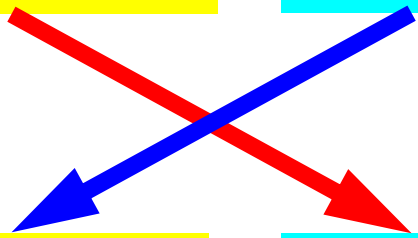
```
for (neib=0; neib<NeibPETot;neib++){
   for (k=export_index[neib];k<export_index[neib+1];k++){
      kk= export_item[k];
      SendBuf[k]= VAL[kk];
   }
}

for (neib=0; neib<NeibPETot; neib++){
  tag= 0;
  iS_e= export_index[neib];
  iE_e= export_index[neib+1];
  BUFlength_e= iE_e - iS_e

  ierr= MPI_Isend
        (&SendBuf[iS_e], BUFlength_e, MPI_DOUBLE, NeibPE[neib], 0,
         MPI_COMM_WORLD, &ReqSend[neib])
}

MPI_Waitall(NeibPETot, ReqSend, StatSend);
```

Copied to sending buffers

Notice: Send/Recv Arrays

```
#PE0
  send:
    VEC(start_send)~
    VEC(start_send+length_send-1)
```

```
#PE1
  send:
    VEC(start_send)~
    VEC(start_send+length_send-1)
```



```
#PE0
  recv:
    VEC(start_recv)~
    VEC(start_recv+length_recv-1)
```

```
#PE1
  recv:
    VEC(start_recv)~
    VEC(start_recv+length_recv-1)
```

- “length_send” of sending process must be equal to “length_recv” of receiving process.
  - PE#0 to PE#1, PE#1 to PE#0
- “sendbuf” and “recvbuf”: different address

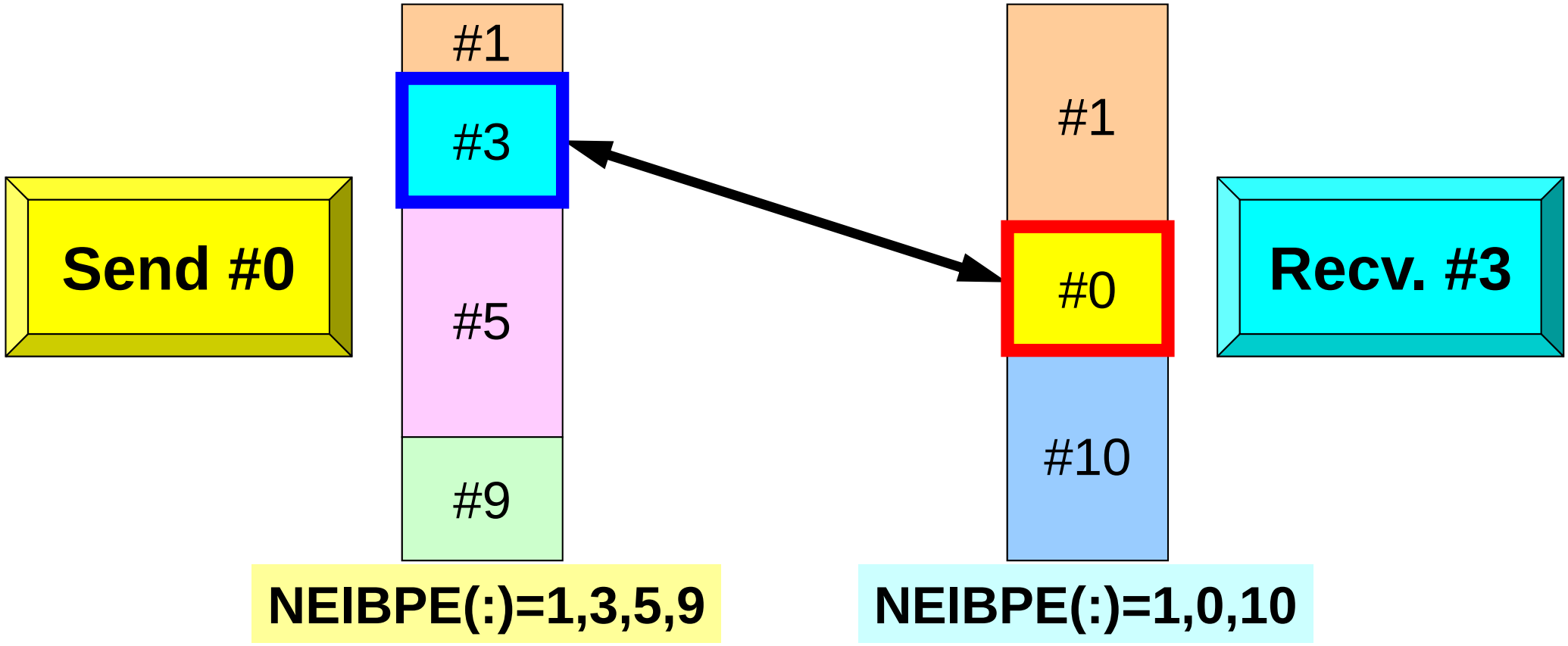
Relationship SEND/RECV

```
 do neib= 1, NEIBPETOT
   iS_e= export_index(neib-1) + 1
   iE_e= export_index(neib  )
   BUFlength_e= iE_e + 1 - iS_e

   call MPI_ISEND                                                  &
&          (SENDbuf(iS_e), BUFlength_e, MPI_INTEGER, NEIBPE(neib), 0,&
&           MPI_COMM_WORLD, request_send(neib), ierr)
  enddo
```

```
 do neib= 1, NEIBPETOT
   iS_i= import_index(neib-1) + 1
   iE_i= import_index(neib  )
   BUFlength_i= iE_i + 1 - iS_i

   call MPI_IRECV                                                  &
&          (RECVbuf(iS_i), BUFlength_i, MPI_INTEGER, NEIBPE(neib), 0,&
&           MPI_COMM_WORLD, request_recv(neib), ierr)
  enddo
```

- Consistency of ID’s of sources/destinations, size and contents of messages !
- Communication occurs when NEIBPE(neib) matches

Relationship SEND/RECV (#0 to #3)



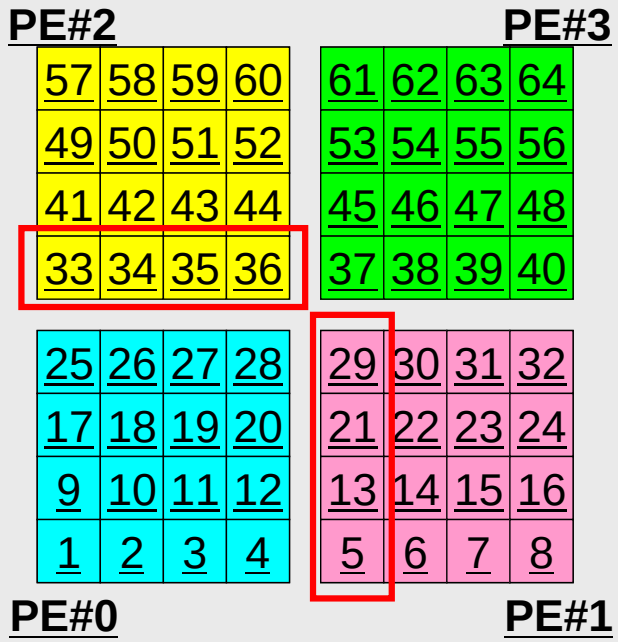
- Consistency of ID’s of sources/destinations, size and contents of messages !
- Communication occurs when NEIBPE(neib) matches

Example: sq-sr1.c (5/6)

C

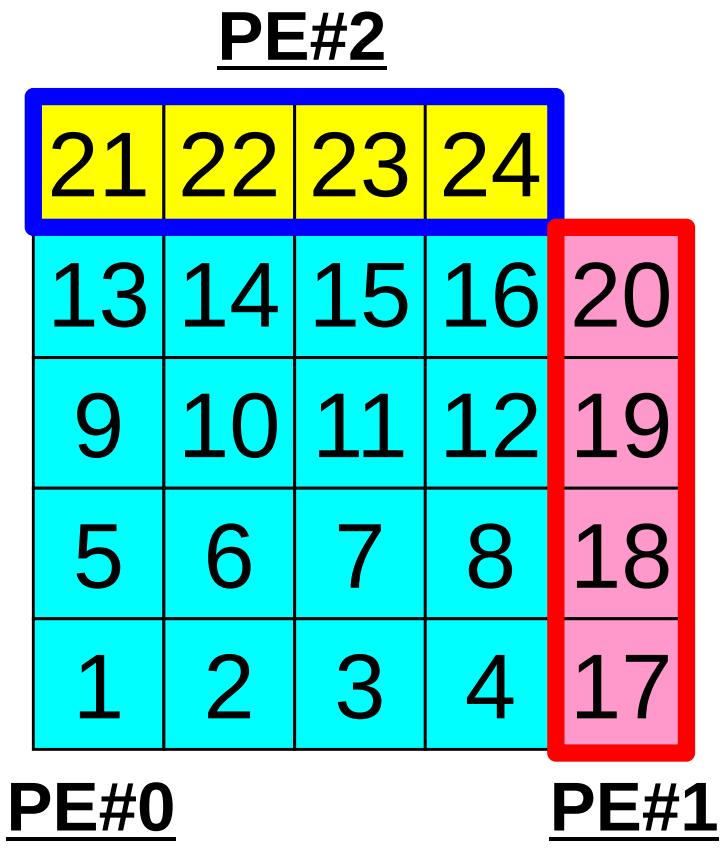
RECV/Import: MPI_Irecv

```
/*
!C
!C +-----------+
!C | SEND-RECV |
!C +-----------+
!C===*/
        StatSend = malloc(sizeof(MPI_Status) * NeibPeTot);
        StatRecv = malloc(sizeof(MPI_Status) * NeibPeTot);
        RequestSend = malloc(sizeof(MPI_Request) * NeibPeTot);
        RequestRecv = malloc(sizeof(MPI_Request) * NeibPeTot);

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ExportIndex[neib];
                iEnd   = ExportIndex[neib+1];
                BufLength = iEnd - iStart;
                MPI_Isend(&SendBuf[iStart], BufLength, MPI_INT,
                                  NeibPe[neib], 0, MPI_COMM_WORLD, &RequestSend[neib]);
        }

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ImportIndex[neib];
                iEnd   = ImportIndex[neib+1];
                BufLength = iEnd - iStart;

                MPI_Irecv(&RecvBuf[iStart], BufLength, MPI_INT,
                                  NeibPe[neib], 0, MPI_COMM_WORLD, &RequestRecv[neib]);
        }
```



RECV/Import: PE#0

```
#NEIBPEtot
2
#NEIBPE
1  2
#NODE
24 16
#IMPORTindex
4  8
#IMPORTitems
17
18
19
20
21
22
23
24
#EXPORTindex
4  8
#EXPORTitems
4
8
12
16
13
14
15
16
```



RECV: MPI_Isend/Irecv/Waitall

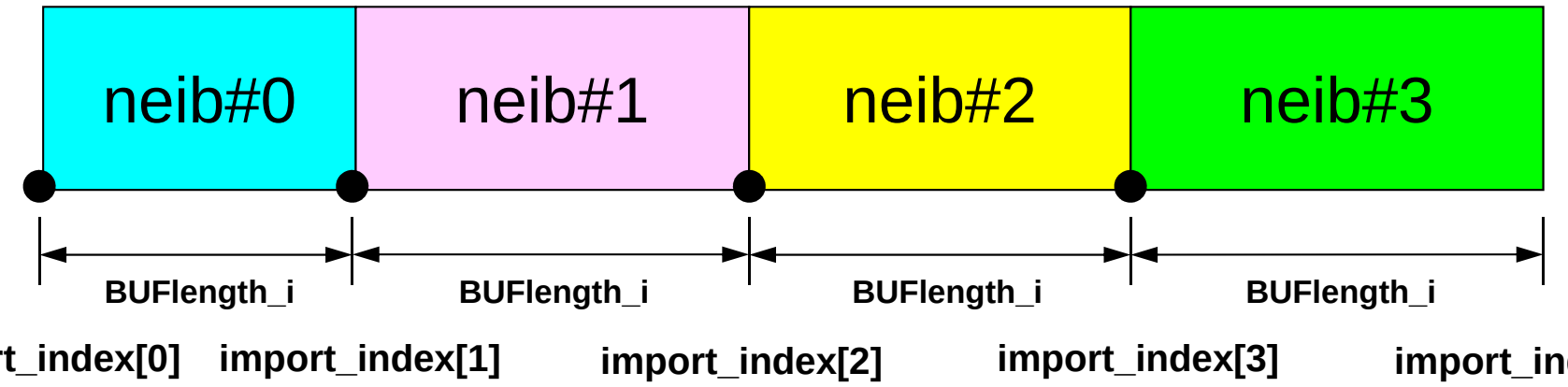
C

```
for (neib=0; neib<NeibPETot; neib++){
   tag= 0;
   iS_i= import_index[neib];
   iE_i= import_index[neib+1];
   BUFlength_i= iE_i - iS_i

   ierr= MPI_Irecv
         (&RecvBuf[iS_i], BUFlength_i, MPI_DOUBLE, NeibPE[neib], 0,
          MPI_COMM_WORLD, &ReqRecv[neib])
}

MPI_Waitall(NeibPETot, ReqRecv, StatRecv);

for (neib=0; neib<NeibPETot;neib++){
    for (k=import_index[neib];k<import_index[neib+1];k++){
       kk= import_item[k];
       VAL[kk]= RecvBuf[k];
    }
}
```

Copied from receiving buffer

import_item (import_index[neib]:import_index[neib+1]-1) are received from neib-th neighbor

RecvBuf



Example: sq-sr1.c (6/6)

C

Reading info of ext pts from receiving buffers

```
        MPI_Waitall(NeibPeTot, RequestRecv, StatRecv);

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ImportIndex[neib];
                iEnd   = ImportIndex[neib+1];
                for(i=iStart;i<iEnd;i++){
                        val[ImportItem[i]] = RecvBuf[i];
                }
        }
        MPI_Waitall(NeibPeTot, RequestSend, StatSend); /*

!C +--------+
!C | OUTPUT |
!C +--------+
!C===*/
        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ImportIndex[neib];
                iEnd   = ImportIndex[neib+1];
                for(i=iStart;i<iEnd;i++){
                        int in = ImportItem[i];
                        printf("RECVbuf%8d%8d%8d¥n", MyRank, NeibPe[neib], val[in]);
                }
        }
        MPI_Finalize();

        return 0;
}
```

Contents of **RecvBuf** are copied to values at external points.

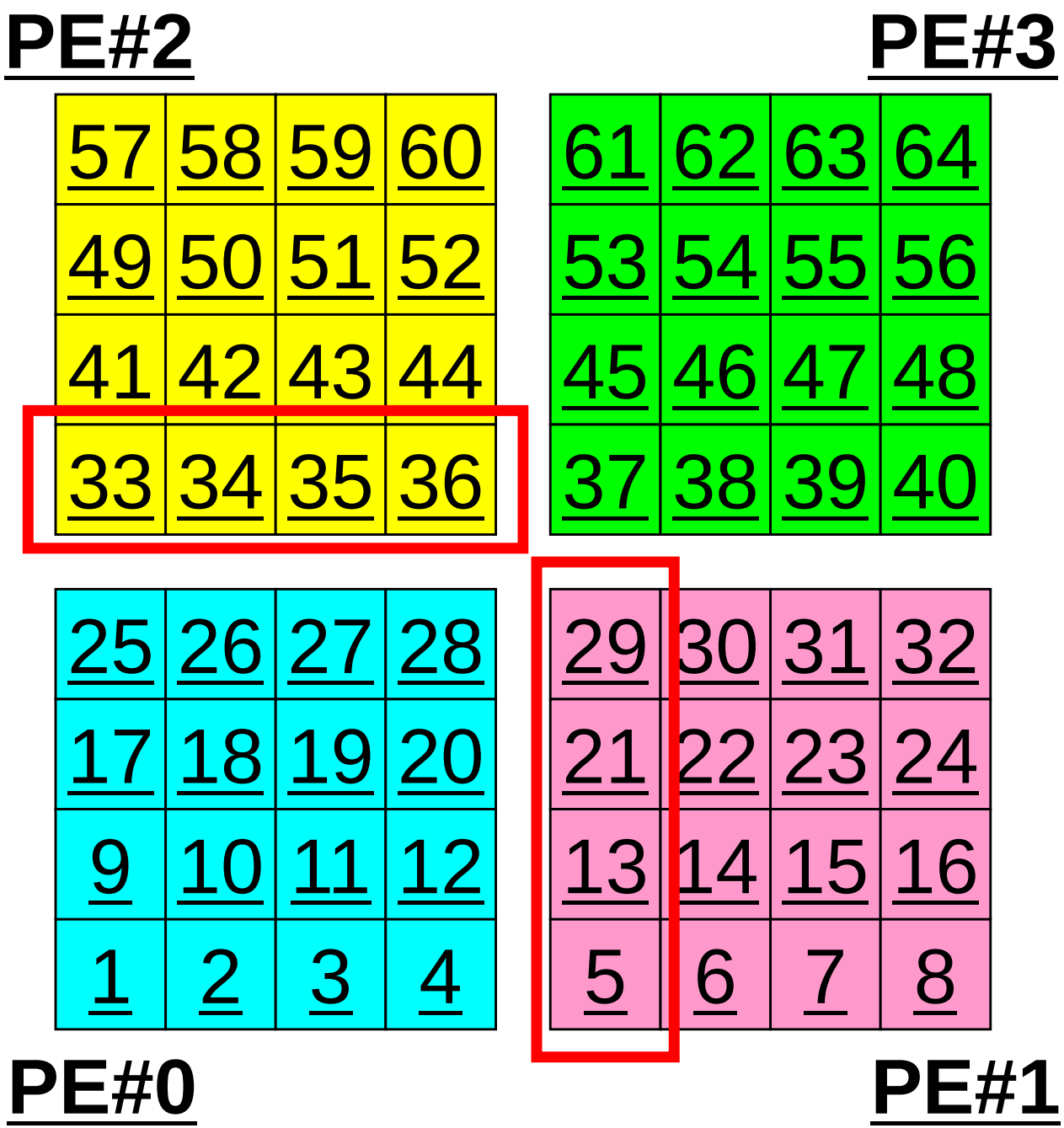
Example: sq-sr1.c (6/6)

C

Writing values at external points

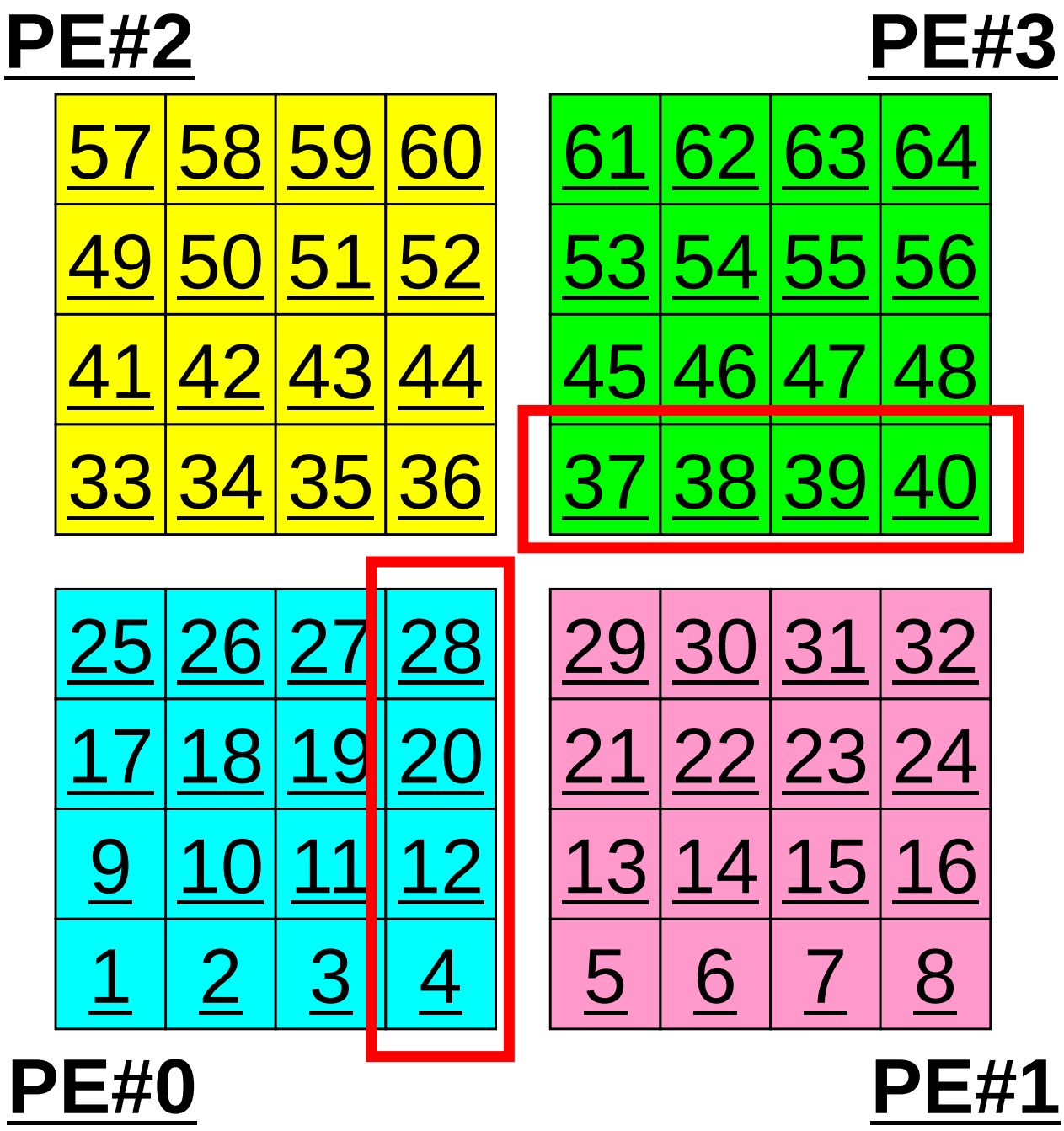
```
        MPI_Waitall(NeibPeTot, RequestRecv, StatRecv);

        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ImportIndex[neib];
                iEnd   = ImportIndex[neib+1];
                for(i=iStart;i<iEnd;i++){
                        val[ImportItem[i]] = RecvBuf[i];
                }
        }
        MPI_Waitall(NeibPeTot, RequestSend, StatSend); /*

!C +--------+
!C | OUTPUT |
!C +--------+
!C===*/
        for(neib=0;neib<NeibPeTot;neib++){
                iStart = ImportIndex[neib];
                iEnd   = ImportIndex[neib+1];
                for(i=iStart;i<iEnd;i++){
                        int in = ImportItem[i];
                        printf("RECVbuf%8d%8d%8d¥n", MyRank, NeibPe[neib], val[in]);
                }
        }
        MPI_Finalize();

        return 0;
}
```

Results (PE#0)



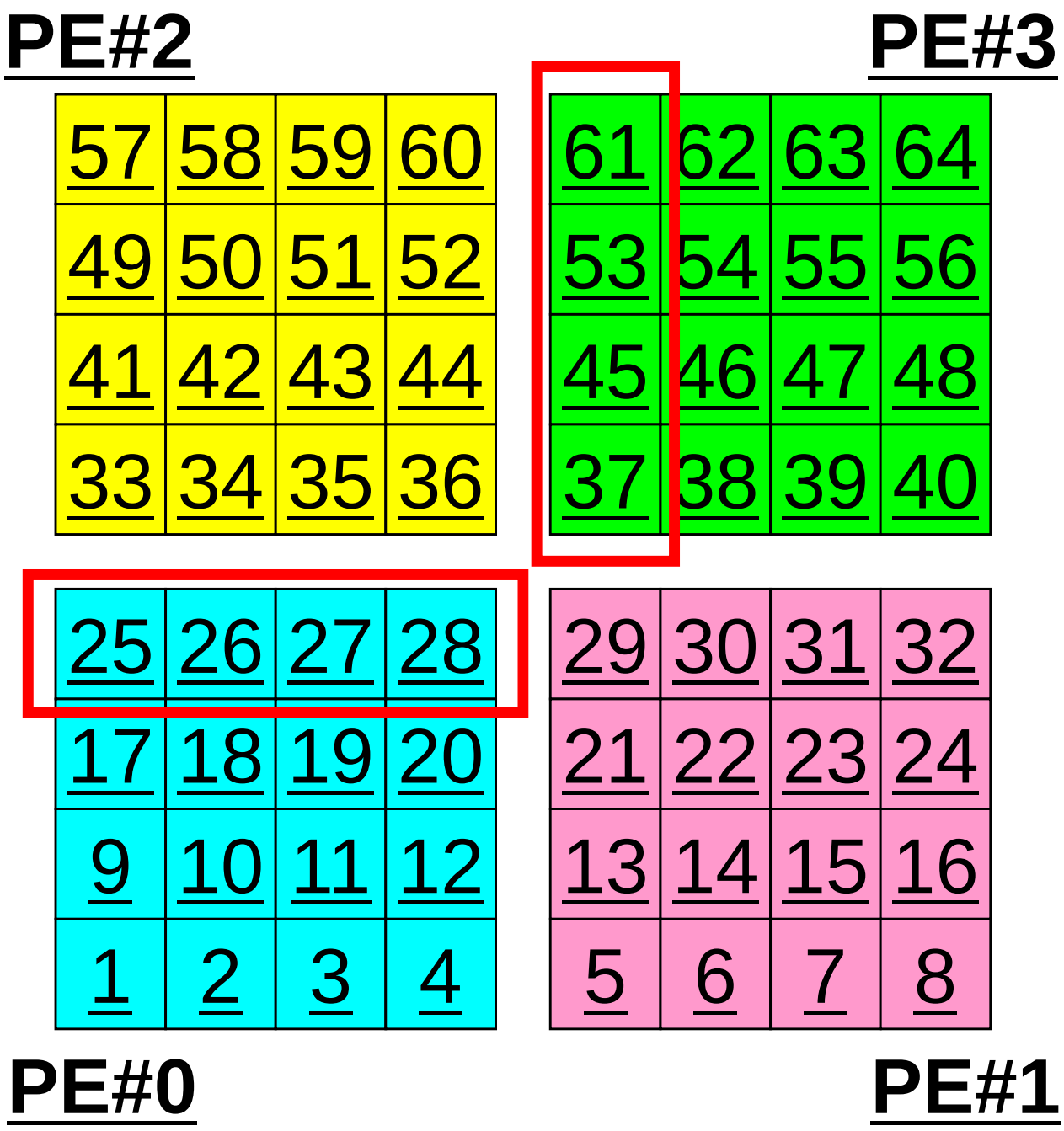

```
RECVbuf         0         1          5
RECVbuf         0         1         13
RECVbuf         0         1         21
RECVbuf         0         1         29
RECVbuf         0         2         33
RECVbuf         0         2         34
RECVbuf         0         2         35
RECVbuf         0         2         36

RECVbuf         1         0          4
RECVbuf         1         0         12
RECVbuf         1         0         20
RECVbuf         1         0         28
RECVbuf         1         3         37
RECVbuf         1         3         38
RECVbuf         1         3         39
RECVbuf         1         3         40

RECVbuf         2         3         37
RECVbuf         2         3         45
RECVbuf         2         3         53
RECVbuf         2         3         61
RECVbuf         2         0         25
RECVbuf         2         0         26
RECVbuf         2         0         27
RECVbuf         2         0         28

RECVbuf         3         2         36
RECVbuf         3         2         44
RECVbuf         3         2         52
RECVbuf         3         2         60
RECVbuf         3         1         29
RECVbuf         3         1         30
RECVbuf         3         1         31
RECVbuf         3         1         32
```

Results (PE#1)



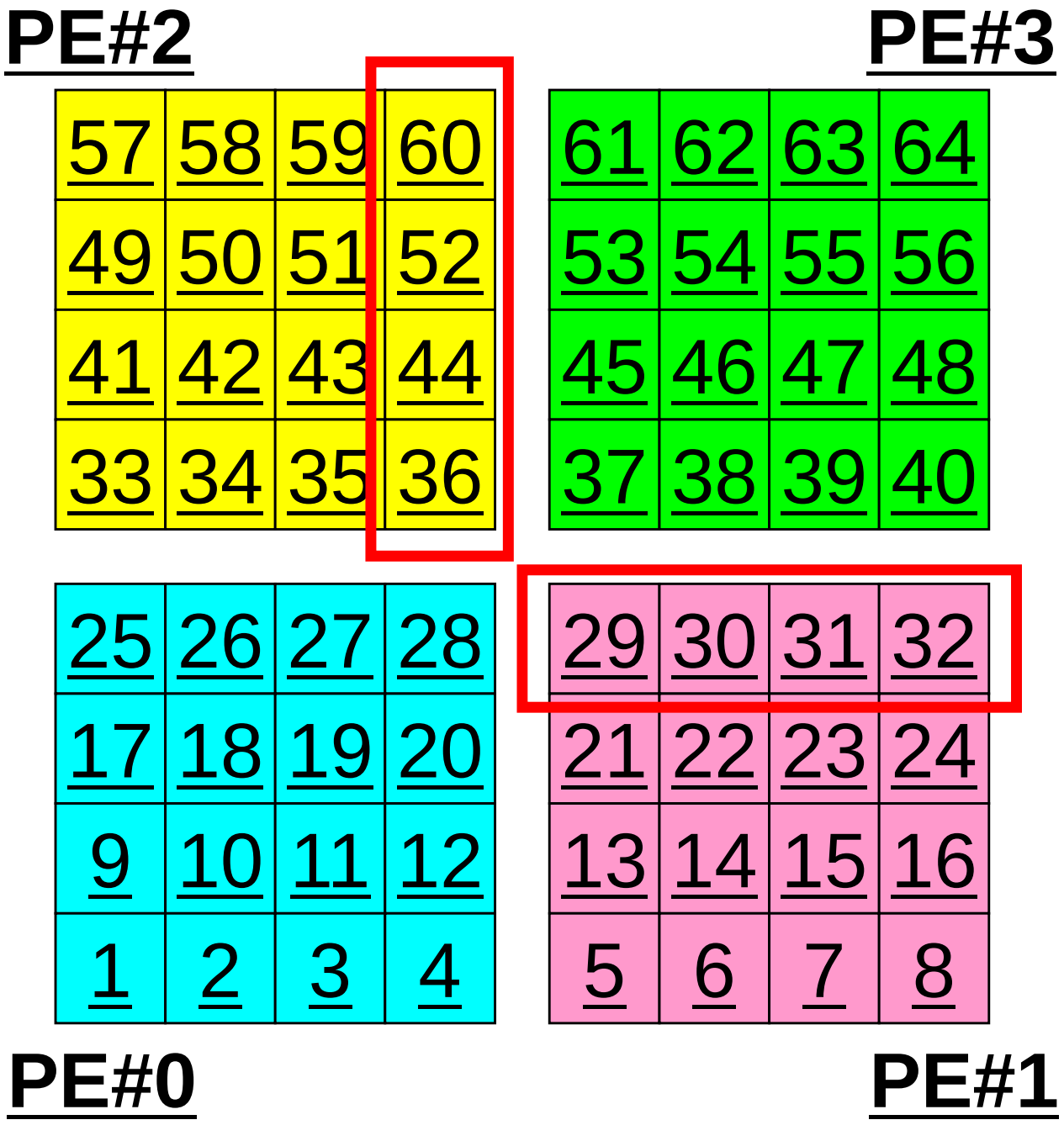

```
RECVbuf      0      1       5
RECVbuf      0      1      13
RECVbuf      0      1      21
RECVbuf      0      1      29
RECVbuf      0      2      33
RECVbuf      0      2      34
RECVbuf      0      2      35
RECVbuf      0      2      36

RECVbuf      1      0       4
RECVbuf      1      0      12
RECVbuf      1      0      20
RECVbuf      1      0      28
RECVbuf      1      3      37
RECVbuf      1      3      38
RECVbuf      1      3      39
RECVbuf      1      3      40

RECVbuf      2      3      37
RECVbuf      2      3      45
RECVbuf      2      3      53
RECVbuf      2      3      61
RECVbuf      2      0      25
RECVbuf      2      0      26
RECVbuf      2      0      27
RECVbuf      2      0      28

RECVbuf      3      2      36
RECVbuf      3      2      44
RECVbuf      3      2      52
RECVbuf      3      2      60
RECVbuf      3      1      29
RECVbuf      3      1      30
RECVbuf      3      1      31
RECVbuf      3      1      32
```

Results (PE#2)




```
RECVbuf      0      1       5
RECVbuf      0      1      13
RECVbuf      0      1      21
RECVbuf      0      1      29
RECVbuf      0      2      33
RECVbuf      0      2      34
RECVbuf      0      2      35
RECVbuf      0      2      36

RECVbuf      1      0       4
RECVbuf      1      0      12
RECVbuf      1      0      20
RECVbuf      1      0      28
RECVbuf      1      3      37
RECVbuf      1      3      38
RECVbuf      1      3      39
RECVbuf      1      3      40

RECVbuf      2      3      37
RECVbuf      2      3      45
RECVbuf      2      3      53
RECVbuf      2      3      61
RECVbuf      2      0      25
RECVbuf      2      0      26
RECVbuf      2      0      27
RECVbuf      2      0      28

RECVbuf      3      2      36
RECVbuf      3      2      44
RECVbuf      3      2      52
RECVbuf      3      2      60
RECVbuf      3      1      29
RECVbuf      3      1      30
RECVbuf      3      1      31
RECVbuf      3      1      32
```

Results (PE#3)




```
RECVbuf      0      1       5
RECVbuf      0      1      13
RECVbuf      0      1      21
RECVbuf      0      1      29
RECVbuf      0      2      33
RECVbuf      0      2      34
RECVbuf      0      2      35
RECVbuf      0      2      36

RECVbuf      1      0       4
RECVbuf      1      0      12
RECVbuf      1      0      20
RECVbuf      1      0      28
RECVbuf      1      3      37
RECVbuf      1      3      38
RECVbuf      1      3      39
RECVbuf      1      3      40

RECVbuf      2      3      37
RECVbuf      2      3      45
RECVbuf      2      3      53
RECVbuf      2      3      61
RECVbuf      2      0      25
RECVbuf      2      0      26
RECVbuf      2      0      27
RECVbuf      2      0      28

RECVbuf      3      2      36
RECVbuf      3      2      44
RECVbuf      3      2      52
RECVbuf      3      2      60
RECVbuf      3      1      29
RECVbuf      3      1      30
RECVbuf      3      1      31
RECVbuf      3      1      32
```

Distributed Local Data Structure for Parallel Computation

- Distributed local data structure for domain-to-doain communications has been introduced, which is appropriate for such applications with sparse coefficient matrices (e.g. FDM, FEM, FVM etc.).
  - SPMD
  - Local Numbering: Internal pts to External pts
  - Generalized communication table

- Everything is easy, if proper data structure is defined:
  - Values at boundary pts are copied into sending buffers
  - Send/Recv
  - Values at external pts are updated through receiving buffers

Initial Mesh

t2

21	22	23	24	25
16	17	18	19	20
11	12	13	14	15
6	7	8	9	10
1	2	3	4	5

Three Domains

t2

#PE2

21	22	23	24
16	17	18	19
11	12	13	14
6	7	8	

#PE1

23	24	25
18	19	20
13	14	15
8	9	10
4	5	

#PE0

11	12	13		
6	7	8	9	10
1	2	3	4	5

Three Domains

t2

#PE2

7 21	8 22	9 23	15 24
4 16	5 17	6 18	14 19
1 11	2 12	3 13	13 14
10 6	11 7	12 8	

#PE1

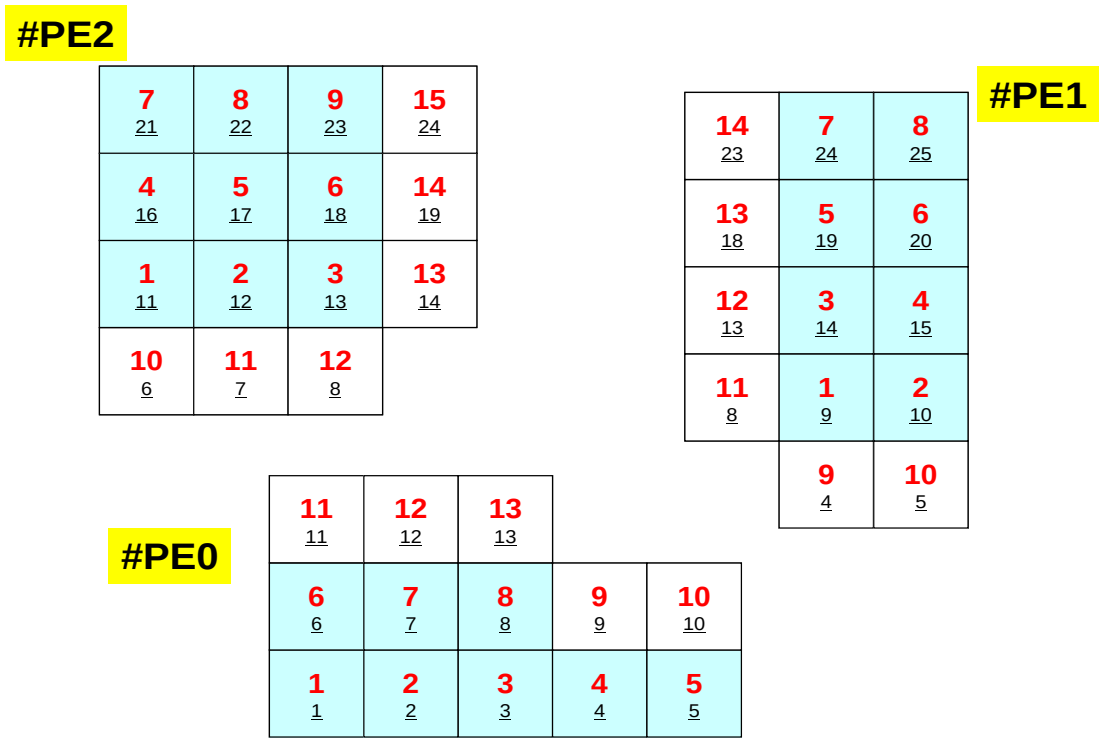
14 23	7 24	8 25
13 18	5 19	6 20
12 13	3 14	4 15
11 8	1 9	2 10
	9 4	10 5

#PE0

11 11	12 12	13 13		
6 6	7 7	8 8	9 9	10 10
1 1	2 2	3 3	4 4	5 5

t2

PE#0: sqm.0: fill ○'s




```
#NEIBPEtot
     2
#NEIBPE
     1     2
#NODE
    13     8   (int+ext, int pts)
#IMPORTindex
     ○     ○
#IMPORTitems
     ○…
#EXPORTindex
     ○     ○
#EXPORTitems
     ○…
```

t2

PE#1: sqm.1: fill ○'s

#PE2

7 21	8 22	9 23	15 24
4 16	5 17	6 18	14 19
1 11	2 12	3 13	13 14
10 6	11 7	12 8	

#PE1

14 23	7 24	8 25
13 18	5 19	6 20
12 13	3 14	4 15
11 8	1 9	2 10
	9 4	10 5

#PE0

11 11	12 12	13 13		
6 6	7 7	8 8	9 9	10 10
1 1	2 2	3 3	4 4	5 5

```
#NEIBPEtot
     2
#NEIBPE
     0     2
#NODE
    14     8 (int+ext, int pts)
#IMPORTindex
     ○     ○
#IMPORTitems
     ○…
#EXPORTindex
     ○     ○
#EXPORTitems
     ○…
```

t2

PE#2: sqm.2: fill ○'s

#PE2

7 21	8 22	9 23	15 24
4 16	5 17	6 18	14 19
1 11	2 12	3 13	13 14
10 6	11 7	12 8	

#PE1

14 23	7 24	8 25
13 18	5 19	6 20
12 13	3 14	4 15
11 8	1 9	2 10
	9 4	10 5

#PE0

11 11	12 12	13 13		
6 6	7 7	8 8	9 9	10 10
1 1	2 2	3 3	4 4	5 5

```
#NEIBPEtot
    2
#NEIBPE
    1    0
#NODE
   15    9 (int+ext, int pts)
#IMPORTindex
    ○    ○
#IMPORTitems
    ○…
#EXPORTindex
    ○    ○
#EXPORTitems
    ○…
```

t2

#PE2

7 21	8 22	9 23	15 24
4 16	5 17	6 18	14 19
1 11	2 12	3 13	13 14
10 6	11 7	12 8	

#PE1

14 23	7 24	8 25
13 18	5 19	6 20
12 13	3 14	4 15
11 8	1 9	2 10
	9 4	10 5

#PE0

11 11	12 12	13 13		
6 6	7 7	8 8	9 9	10 10
1 1	2 2	3 3	4 4	5 5

t2

Procedures

- Number of Internal/External Points
- Where do External Pts come from ?
  - **`IMPORTindex`**, **`IMPORTitems`**
  - Sequence of **`NEIBPE`**
- Then check destinations of Boundary Pts.
  - **`EXPORTindex`**, **`EXPORTitems`**
  - Sequence of **`NEIBPE`**

- “sq.*” are in <$O-S2>/ex
- Create “sqm.*” by yourself
- copy <$O-S2>/a.out (by sq-sr1.c) to <$O-S2>/ex
- qsub go3.sh

Report S2 (1/2)

- Parallelize 1D code (1d.c) using MPI
- Read entire element number, and decompose into sub-domains in your program

- Measure parallel performance

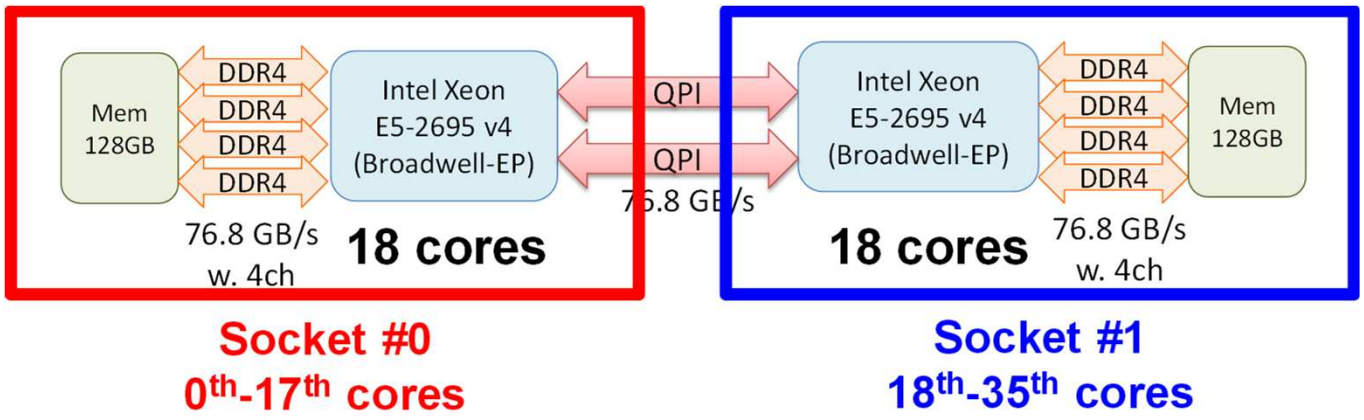
Report S2 (2/2)

- Deadline: January 31st (Tue), 2019, 17:00
  - Send files via e-mail at **nakajima(at)cc.u-tokyo.ac.jp**
- Problem
  - Apply “Generalized Communication Table”
  - Read entire elem. #, decompose into sub-domains in your program
  - Evaluate parallel performance
    - You need huge number of elements, to get excellent performance.
    - Fix number of iterations (e.g. 100), if computations cannot be completed.
- Report
  - Cover Page: Name, ID, and Problem ID (S2) must be written.
  - Less than eight pages including figures and tables (A4).
    - Strategy, Structure of the Program, Remarks
  - Source list of the program (if you have bugs)
  - Output list (as small as possible)

go.sh

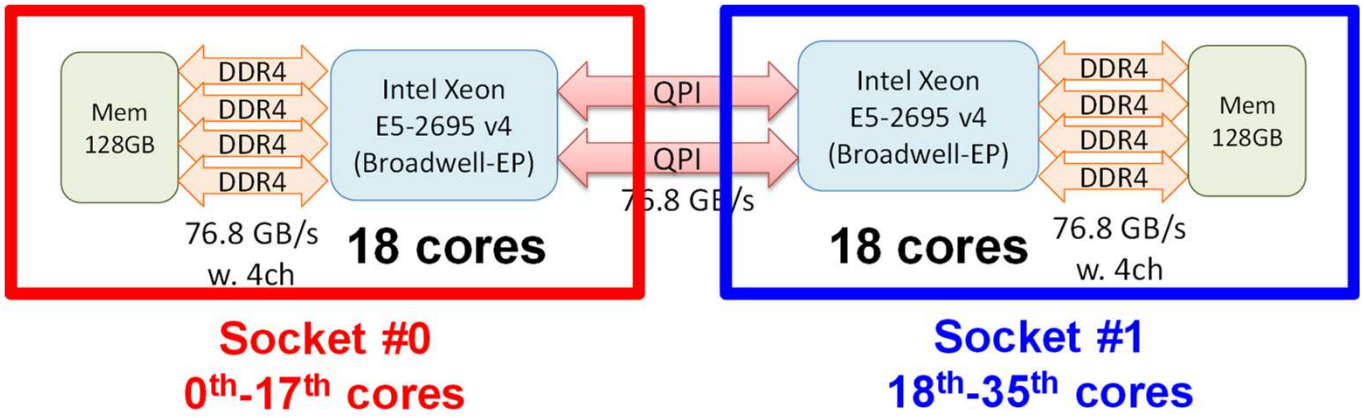
16 cores may be randomly selected from 36 cores

```
#!/bin/sh
#PBS -q u-lecture8                    Name of "QUEUE"
#PBS -N test                          Job Name
#PBS -l select=1:mpiprocs=16          node#, proc#/node
#PBS -Wgroup_list=gt18                Group Name (Wallet)
#PBS -l walltime=00:05:00             Computation Time
#PBS -e err                           Standard Error
#PBS -o test.lst                      Standard Outpt

cd $PBS_O_WORKDIR                     go to current dir
. /etc/profile.d/modules.sh           (ESSENTIAL)

export I_MPI_PIN_DOMAIN=socket        Execution on each socket
export I_MPI_PERHOST=16               =mpiprocs, stable
mpirun ./impimap.sh ./a.out           Exec's
```



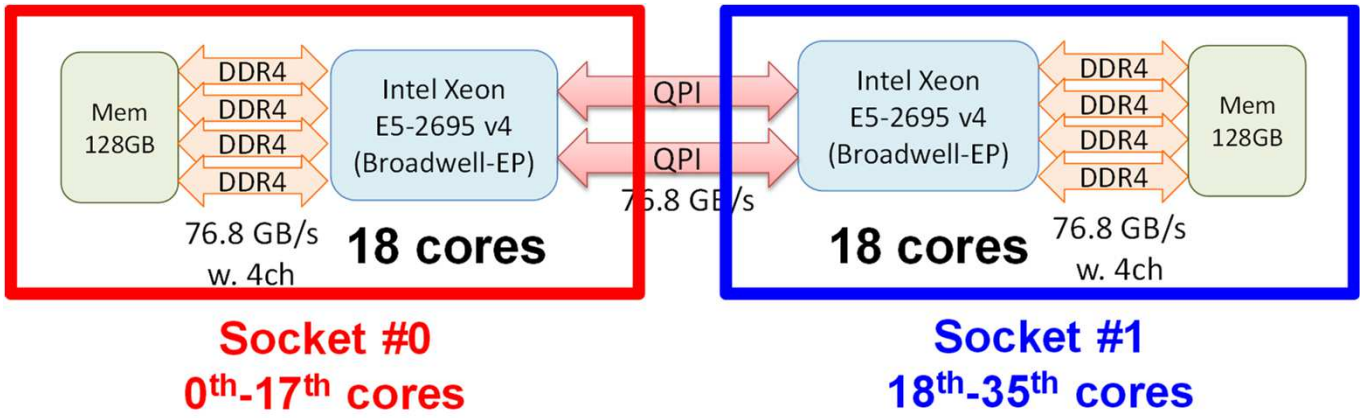
a16.sh: Use 16 cores (0-15th)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=16     MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t16.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0-15   use 0-15th core
mpirun ./impimap.sh ./a.out
```



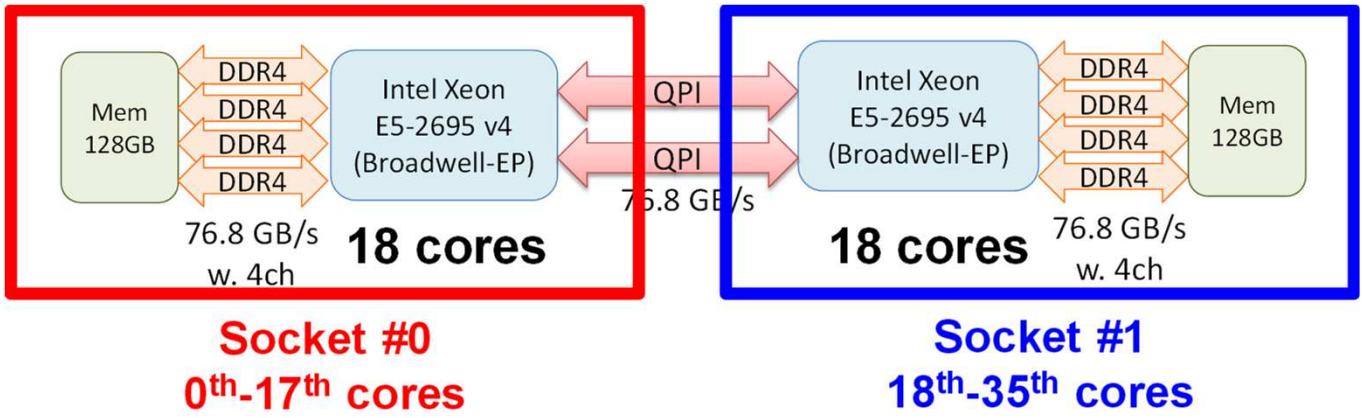
a01.sh: Use 1 core (0th)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=1      MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t01.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0      use 0th core
mpirun ./impimap.sh ./a.out
```



a32.sh: Use 32 cores (16 ea)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=32     MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t32.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0-15,18-33
mpirun ./impimap.sh ./a.out
```



s36.sh: Use 36 cores (ALL)

```
#!/bin/sh

#PBS -q u-lecture8
#PBS -N test
#PBS -l select=1:mpiprocs=36     MPI Process # (1-36)
#PBS -Wgroup_list=gt18
#PBS -l walltime=00:05:00
#PBS -e err
#PBS -o t36.lst

cd $PBS_O_WORKDIR
. /etc/profile.d/modules.sh

export I_MPI_PIN_PROCESSOR_LIST=0-35
mpirun ./impimap.sh ./a.out
```