Report S2
Fortran

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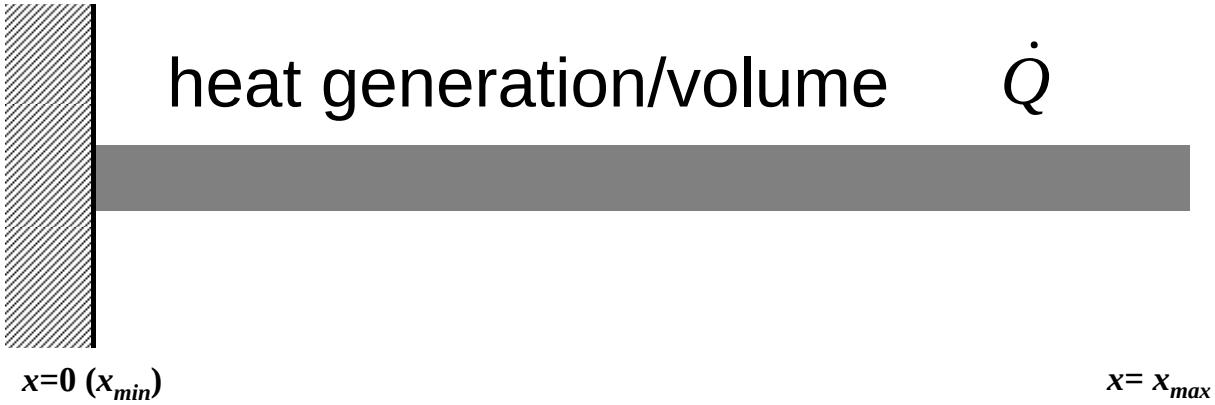
Programming for Parallel Computing (616-2057)
Seminar on Advanced Computing (616-4009)

- Overview
- Distributed Local Data
- Program
- Results

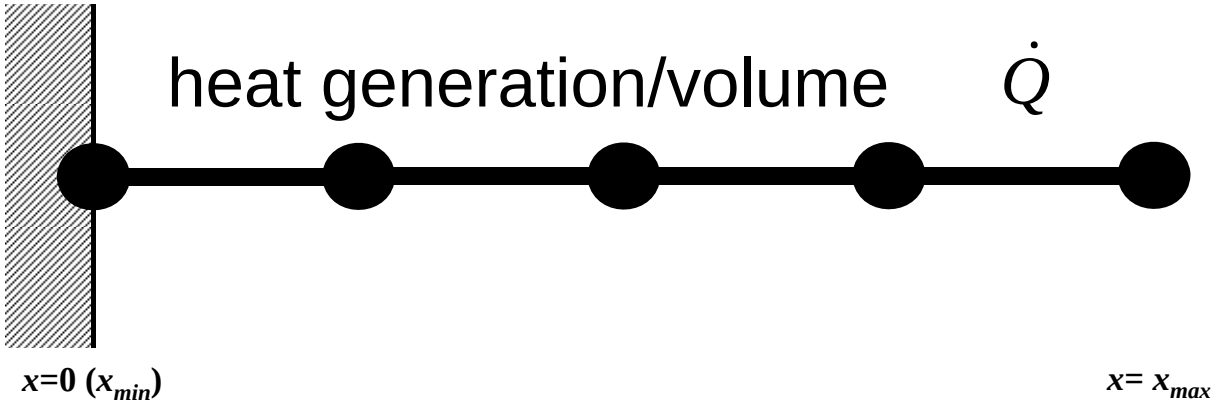
1D Steady State Heat Conduction



$$\frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right)+\dot{Q}=0$$

- Uniform: Sectional Area: A, Thermal Conductivity: λ
- Heat Generation Rate/Volume/Time [$QL^{-3}T^{-1}$] $\dot{Q}$
- Boundary Conditions
  - x=0 : T= 0 (Fixed Temperature)
  - x=x_{max} : $\frac{\partial T}{\partial x}=0$ (Insulated)

1D Steady State Heat Conduction



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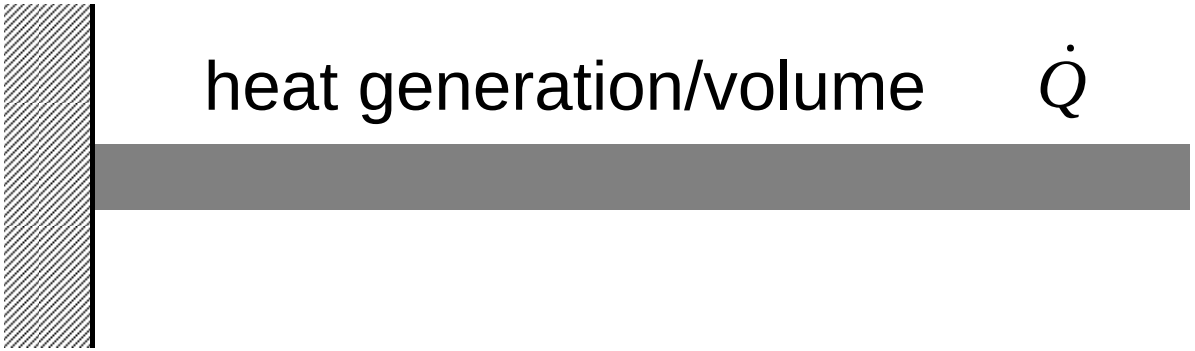
Analytical Solution



$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\dot{Q}=0$$

$$T=0 @ x=0$$

$$\frac{\partial T}{\partial x}=0 @ x=x_{\max}$$

$$\lambda T''=-\dot{Q}$$

$$\lambda T'=-\dot{Q}x+C_1 \Rightarrow C_1=\dot{Q}x_{\max}, \quad T'=0 @ x=x_{\max}$$

$$\lambda T=-\frac{1}{2}\dot{Q}x^2+C_1x+C_2 \Rightarrow C_2=0, \quad T=0 @ x=0$$

$$\therefore \quad T=-\frac{1}{2\lambda}\dot{Q}x^2+\frac{\dot{Q}x_{\max}}{\lambda}x$$

Copy and Compile

Fortran

```
>$ cd <$O-TOP>
>$ cp /home/z30088/class_eps/F/s2r-f.tar .
>$ tar xvf s2r-f.tar
```

C

```
>$ cd <$O-TOP>
>$ cp /home/z30088/class_eps/C/s2r-c.tar .
>$ tar xvf s2r-c.tar
```

Confirm/Compile

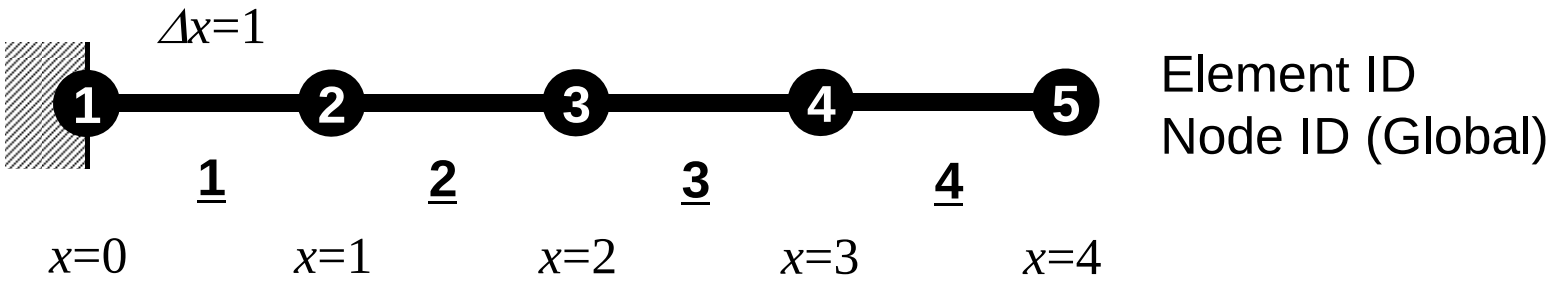
```
 >$ cd mpi/S2-ref
 >$ mpifrtpx –Kfast 1d.f
 >$ mpifccpx –Kfast 1d.c
```

<$O-S2r> = <$O-TOP>/mpi/S2-ref

Control File: input.dat

Control Data `input.dat`

`4`	`NE` (Number of Elements)
`1.0  1.0  1.0  1.0`	Δx (Length of Each Elem.: `L`) , `Q, A,` λ
`100`	Number of MAX. Iterations for CG Solver
`1.e-8`	Convergence Criteria for CG Solver



go.sh

```
#!/bin/sh
#PJM -L “node=4“                  Node # (.le.12)
#PJM -L “elapse=00:10:00“         Comp.Time (.le.15min)
#PJM -L “rscgrp=lecture“          “Queue” (or lecture1)
#PJM -g “gt71“                    “Wallet”
#PJM -
#PJM -o “test.lst“                Standard Output
#PJM --mpi “proc=64“              MPI Process # (.le.192)

mpiexec ./a.out
```

N=8	N=16	N=32	N=64	N=192
“node=1“	“node=1“	“node=2“	“node=4“	“node=12“
“proc=8”	“proc=16”	“proc=32”	“proc=64”	“proc=192”

Procedures for Parallel FEM

- Reading control file, entire element number etc.
- Creating “distributed local data” in the program
- Assembling local and global matrices for linear solvers
- Solving linear equations by CG

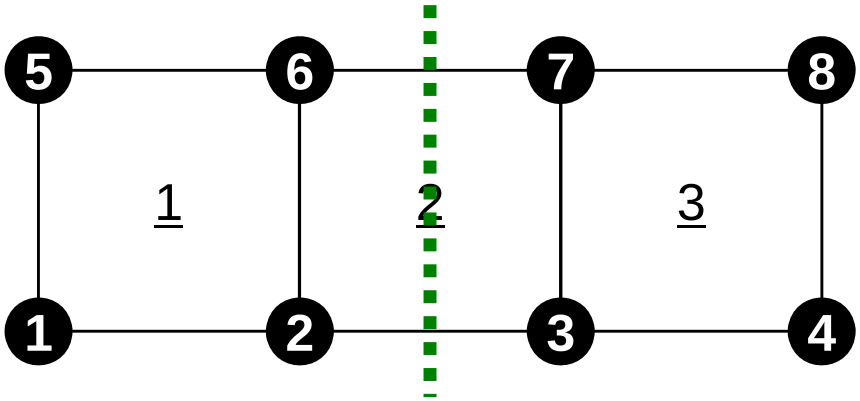
- Not so different from those of original code

- Overview
- **Distributed Local Data**
- Program
- Results

Finite Element Procedures

- Initialization
  - Control Data
  - Node, Connectivity of Elements (N: Node#, NE: Elem#)
  - Initialization of Arrays (Global/Element Matrices)
  - Element-Global Matrix Mapping (Index, Item)
- Generation of Matrix
  - Element-by-Element Operations (do icel= 1, NE)
    - Element matrices
    - Accumulation to global matrix
  - Boundary Conditions
- Linear Solver
  - Conjugate Gradient Method

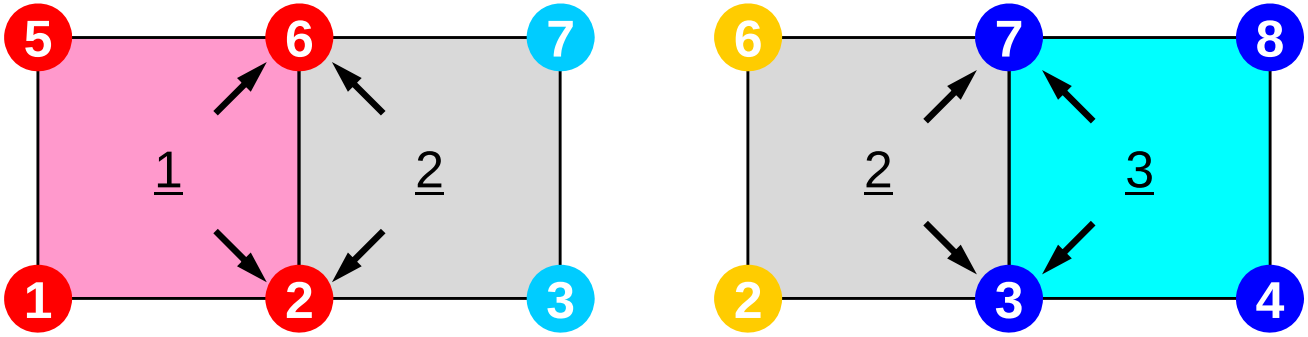
Quadrilateral Elements



Node-based partitioning

Independent variables are defined at nodes (vertices).

Information is not sufficient for assembling coefficient matrices.



Info. of nodes and elements in overlapped zones are required for assembling coef. matrices.

Computation of stress components needs same info.

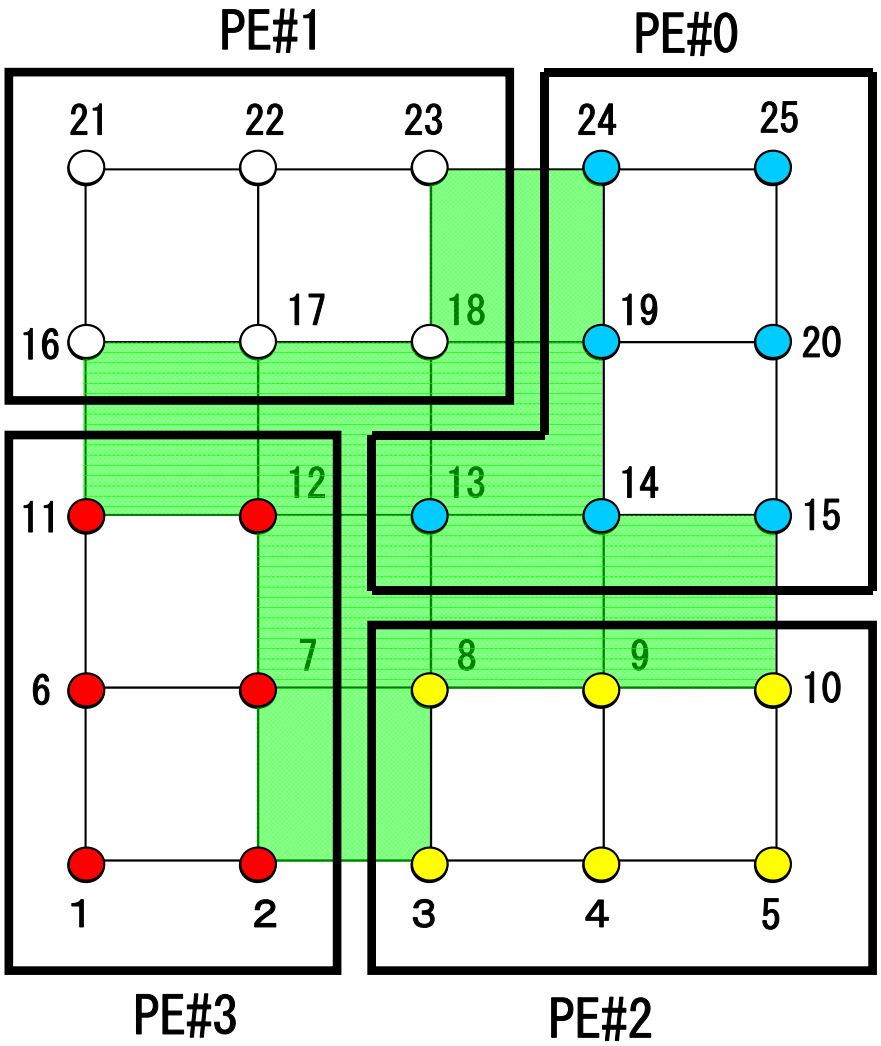
Distributed Local Data Structure for Parallel FEM

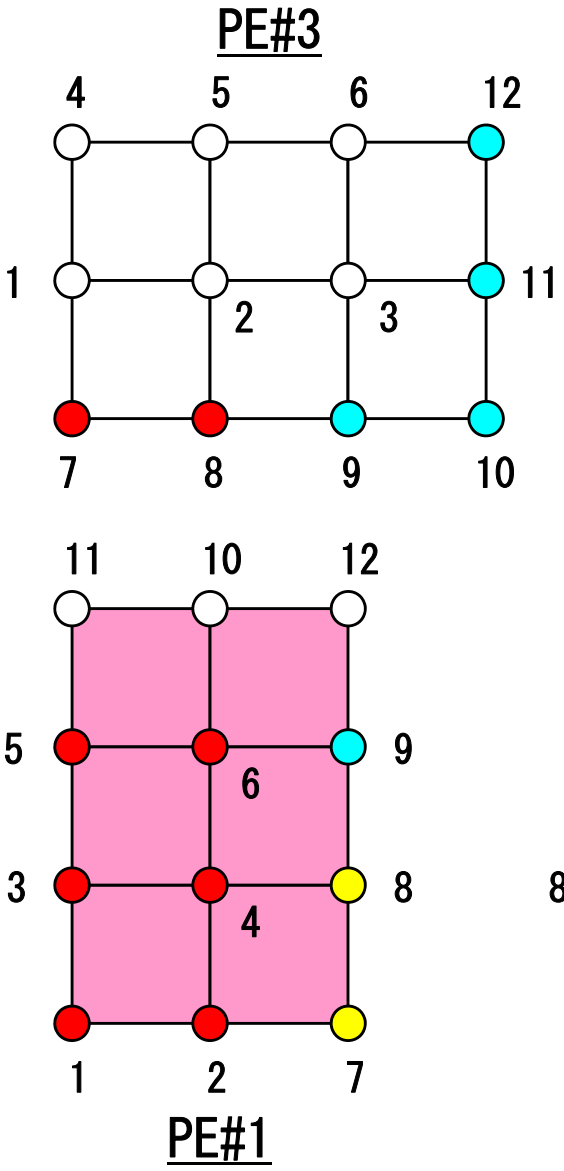
- Node-based partitioning
- Local data includes:
  - Nodes originally assigned to the domain/PE/partition
  - Elements which include above nodes
  - Nodes which are included above elements, and originally NOT-assigned to the domain/PE/partition
- 3 categories for nodes
  - Internal nodes Nodes originally assigned to the domain/PE/partition
  - External nodes Nodes originally NOT-assigned to the domain/PE/partition
  - Boundary nodes External nodes of other domains/PE's/partitions
- Communication tables

- Global info. is not needed except relationship between domains
  - Property of FEM: local element-by-element operations

Node-based Partitioning

internal nodes - elements - external nodes

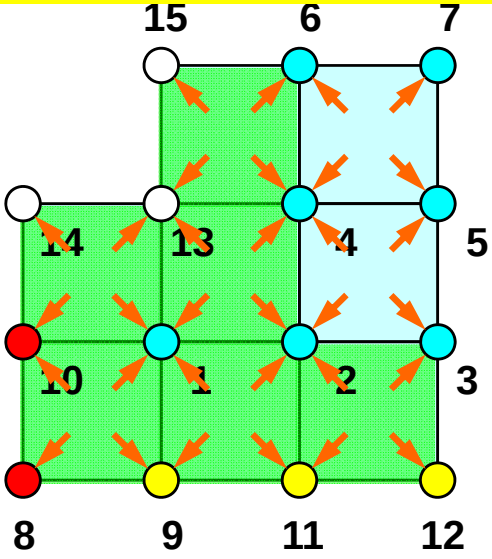


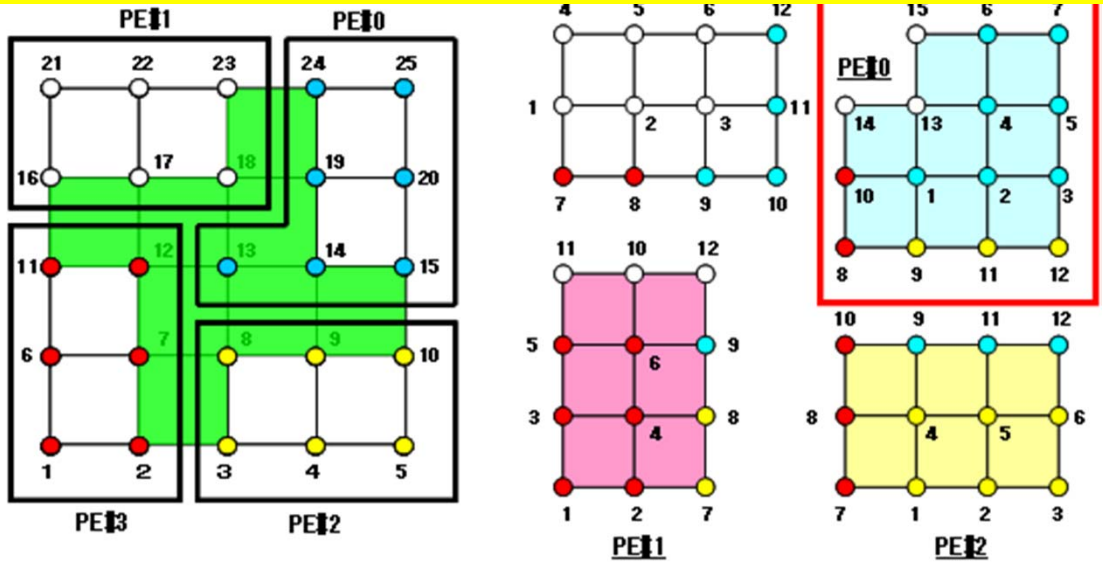


Node-based Partitioning

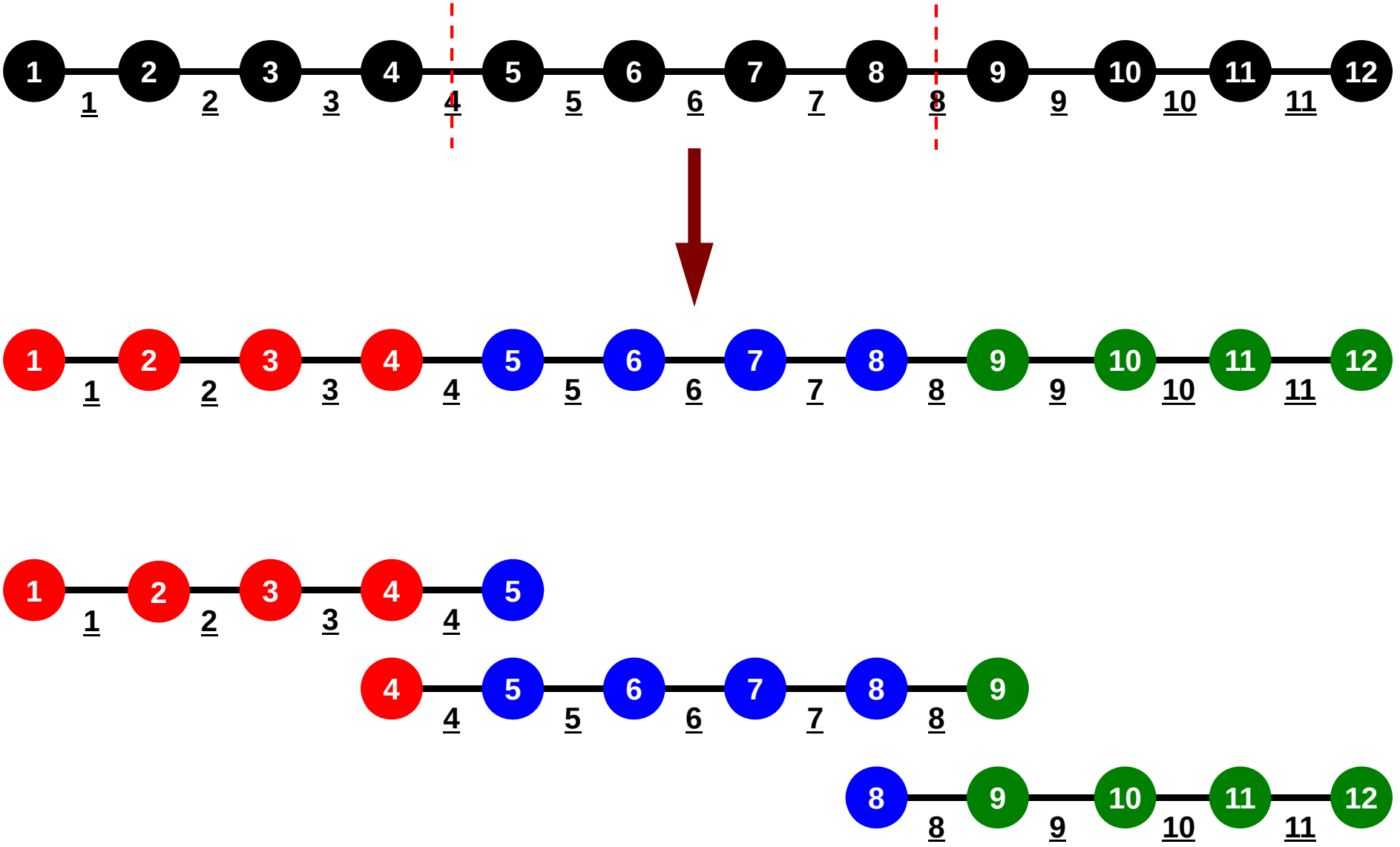
internal nodes - elements - external nodes

- Partitioned nodes themselves (Internal Nodes)　内点
- Elements which include Internal Nodes　内点を含む要素
- External Nodes included in the Elements　外点
  in overlapped region among partitions.
- Info of External Nodes are required for completely local element–based operations on each processor.



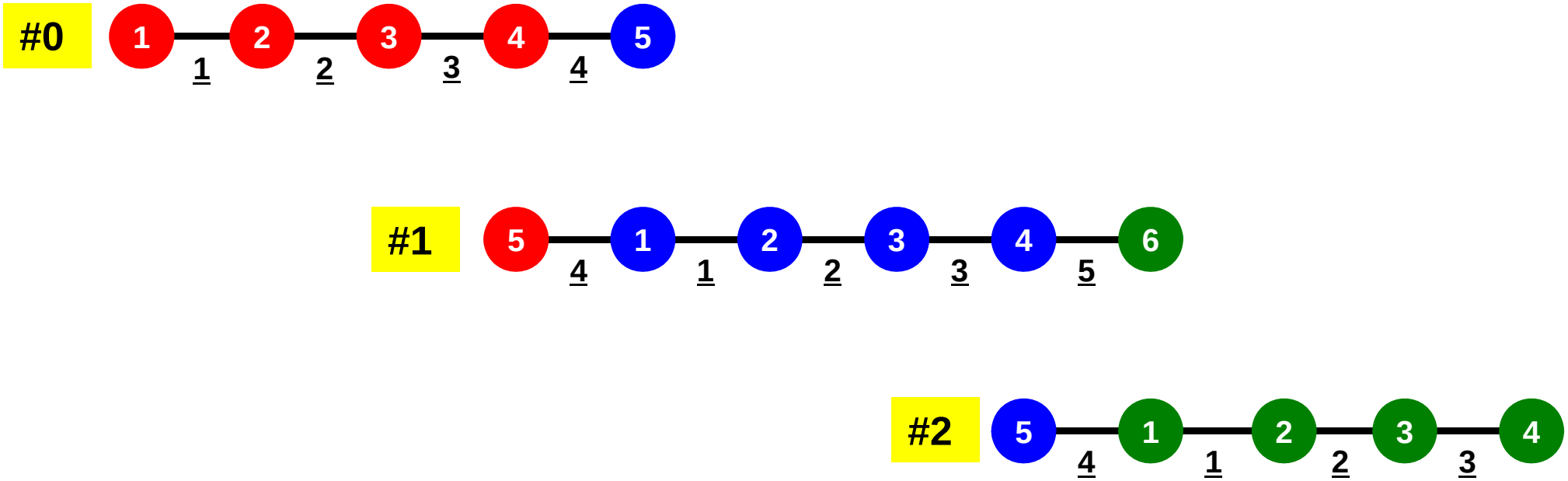


1D FEM: 12 nodes/11 elem's/3 domains



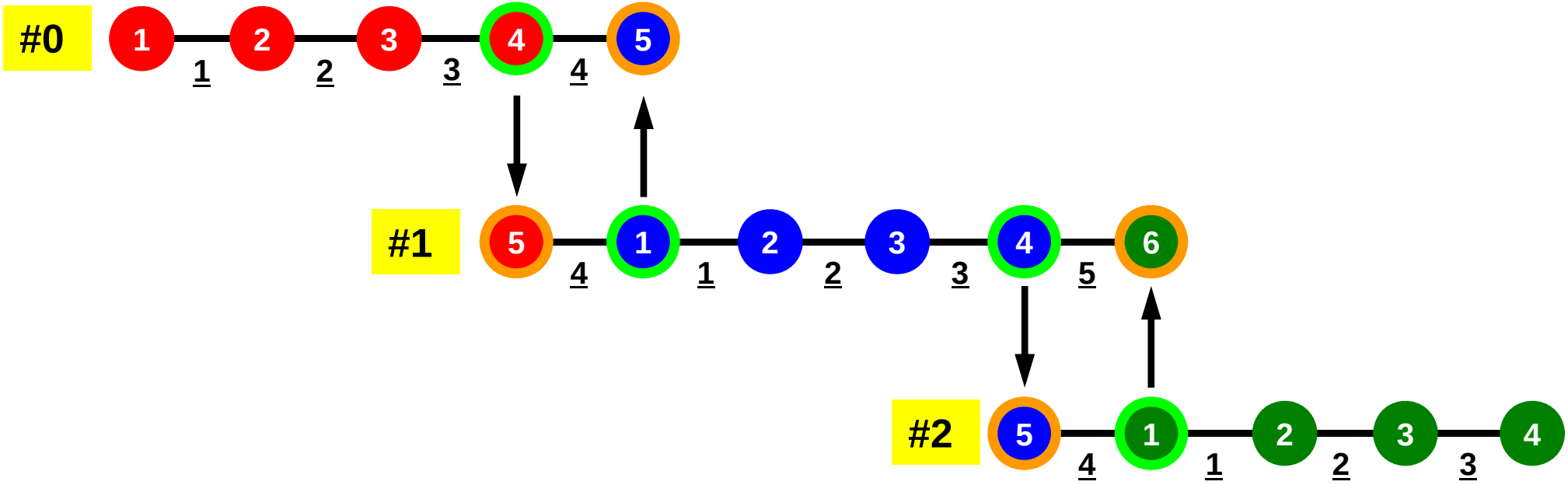
1D FEM: 12 nodes/11 elem's/3 domains

Local ID: Starting from 1 for node and elem at each domain

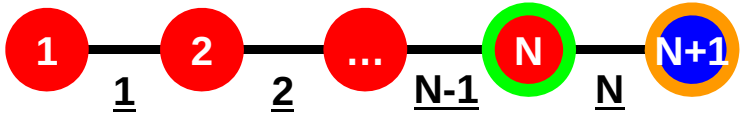


1D FEM: 12 nodes/11 elem's/3 domains

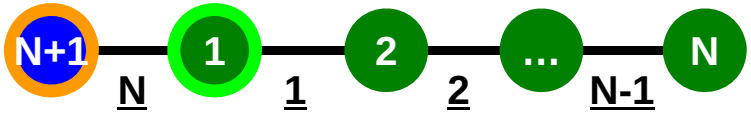
Internal/External Nodes



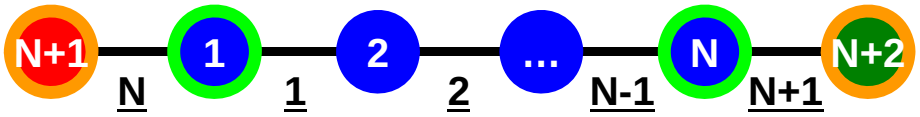
1D FEM: Numbering of Local ID



#0:
N+1 nodes
N elements



#PETot-1:
N+1 nodes
N elements

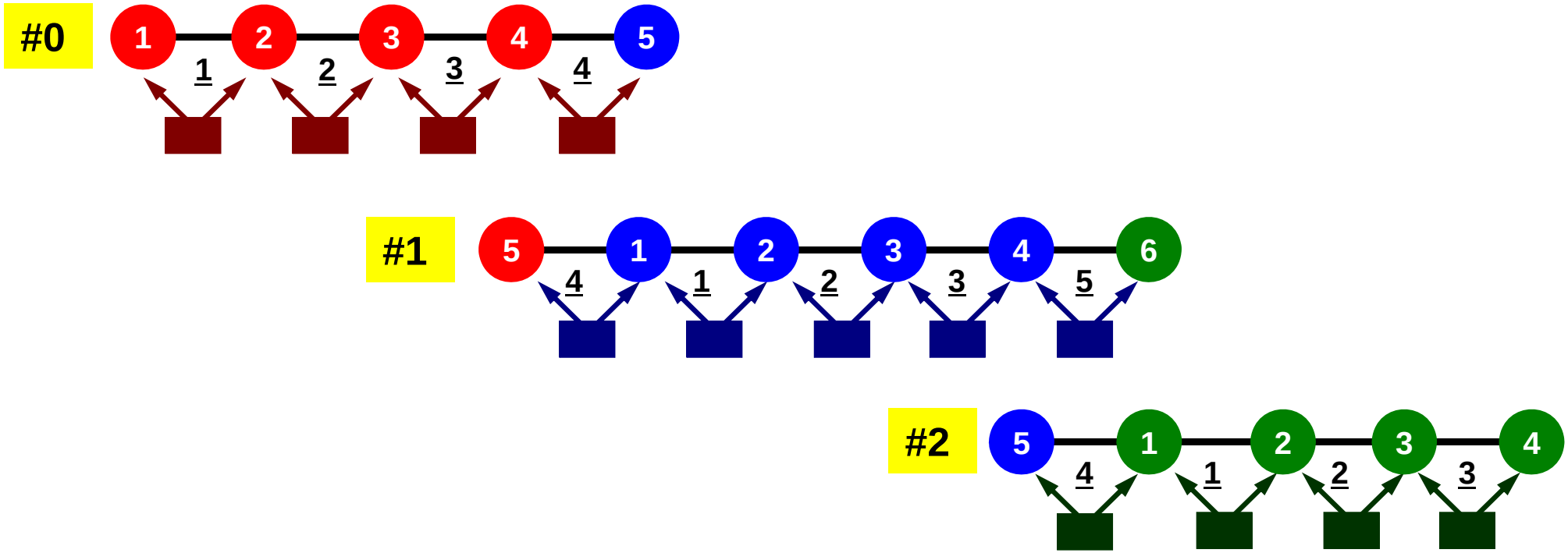


Others (General):
N+2 nodes
N+1 elements

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

Integration on each element, element matrix -> global matrix

Operations can be done by info. of internal/external nodes and elements which include these nodes



Preconditioned Conjugate Gradient Method (CG)

Compute $\mathbf{r^{(0)}= b-[A]x^{(0)}}$
for i= 1, 2, …
  solve $\mathbf{[M]z^{(i-1)}= r^{(i-1)}}$
  $\rho_{i-1}= \mathbf{r^{(i-1)}\ z^{(i-1)}}$
  if i=1
    $p^{(1)}= z^{(0)}$
  else
    $\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
    $p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
  endif
  $\mathbf{q^{(i)}= [A]p^{(i)}}$
  $\alpha_i\ = \rho_{i-1}/\mathbf{p^{(i)}q^{(i)}}$
  $x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$
  $r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$
  check convergence $\mathbf{|r|}$
end

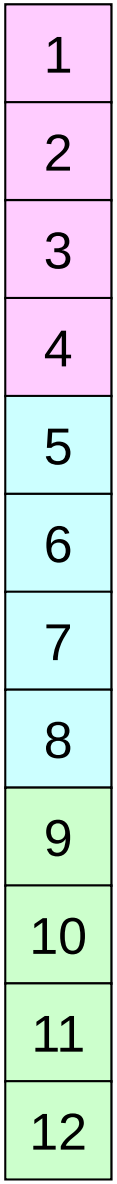
Preconditioning:
Diagonal Scaling
(or Point Jacobi)

Preconditioning, DAXPY

Local Operations by Only Internal Points: Parallel Processing is possible

```
!C
!C-- {z}= [Minv]{r}

      do i= 1, N
        W(i,Z)= W(i,DD) * W(i,R)
      enddo
```

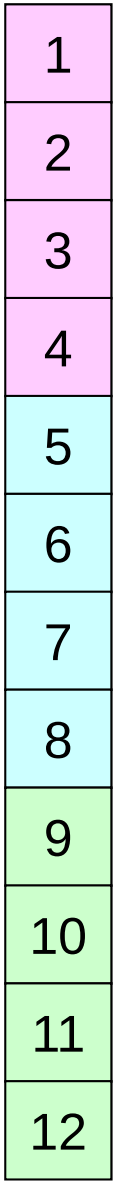
```
!C
!C-- {x}= {x} + ALPHA*{p}
!C   {r}= {r} - ALPHA*{q}

      do i= 1, N
        PHI(i)= PHI(i) + ALPHA * W(i,P)
        W(i,R)= W(i,R) - ALPHA * W(i,Q)
      enddo
```



Dot Products

Global Summation needed: Communication ?

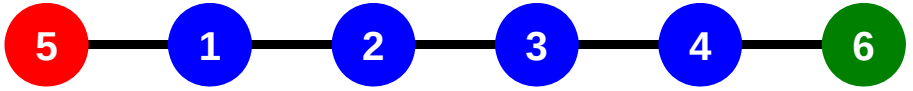
```
!C
!C-- ALPHA= RHO / {p}{q}

      C1= 0.d0
      do i= 1, N
        C1= C1 + W(i,P)*W(i,Q)
      enddo
      ALPHA= RHO / C1
```



Matrix-Vector Products

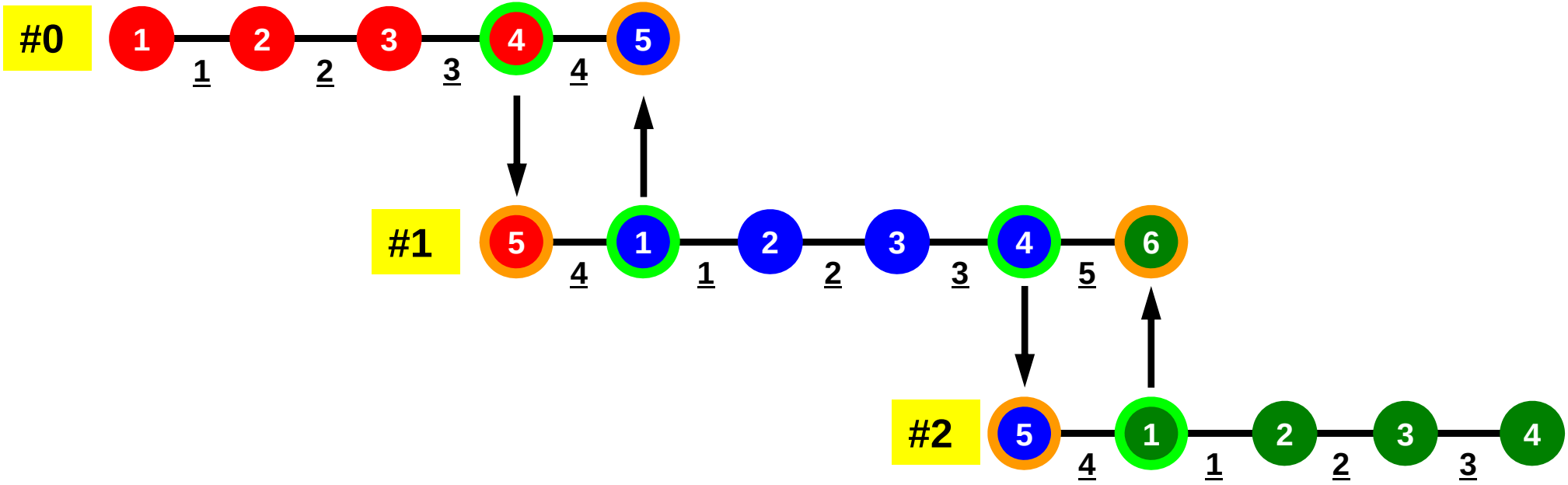
Values at External Points: P-to-P Communication

```
!C
!C-- {q}= [A]{p}

      do i= 1, N
        W(i,Q) = DIAG(i)*W(i,P)
        do j= INDEX(i-1)+1, INDEX(i)
          W(i,Q) = W(i,Q) + AMAT(j)*W(ITEM(j),P)
        enddo
      enddo
```

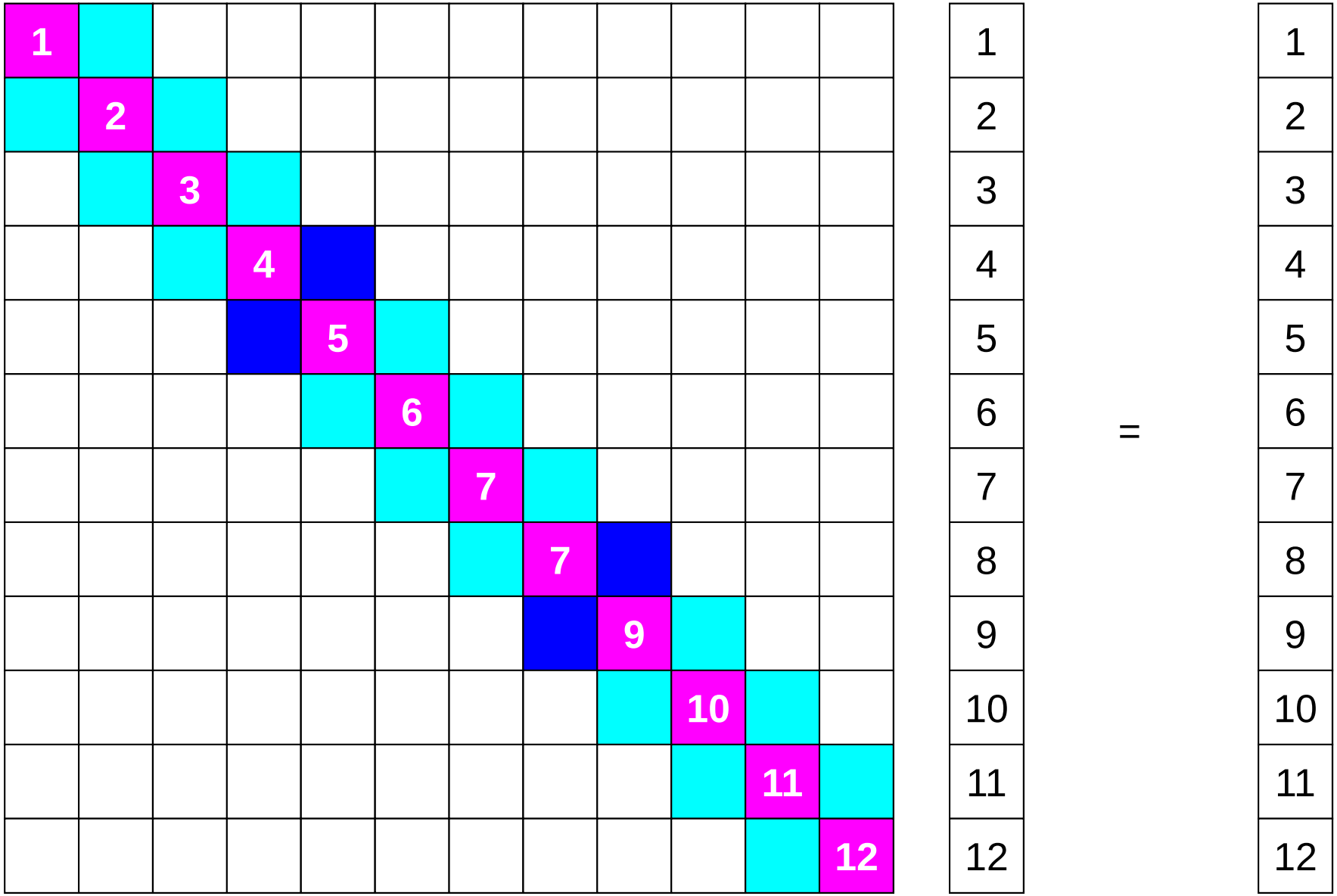


1D FEM: 12 nodes/11 elem's/3 domains

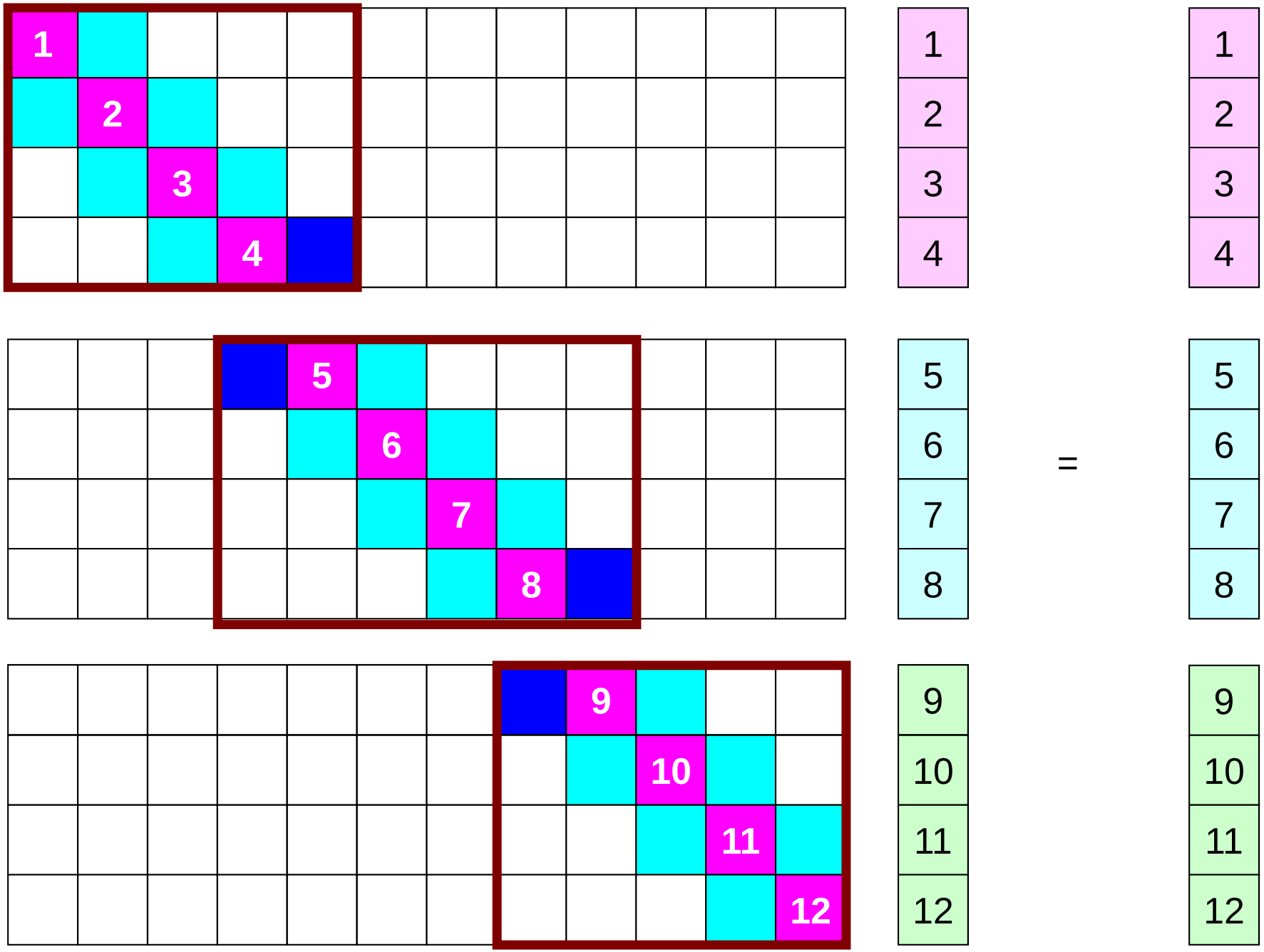
Internal/External Nodes



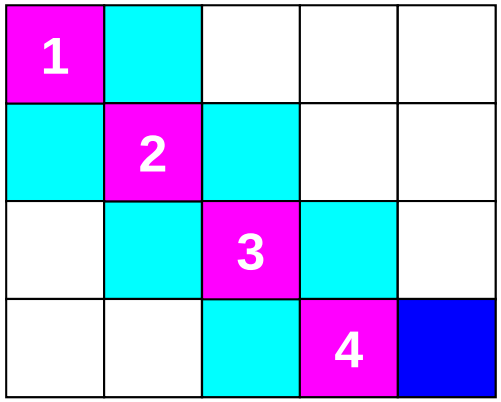
Mat-Vec Products: Local Op. Possible



Mat-Vec Products: Local Op. Possible

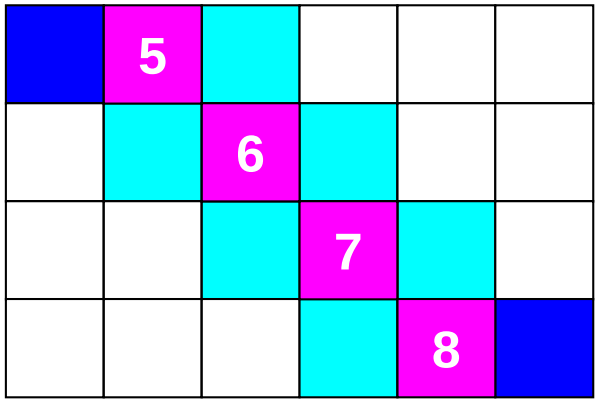


Mat-Vec Products: Local Op. Possible



1
2
3
4

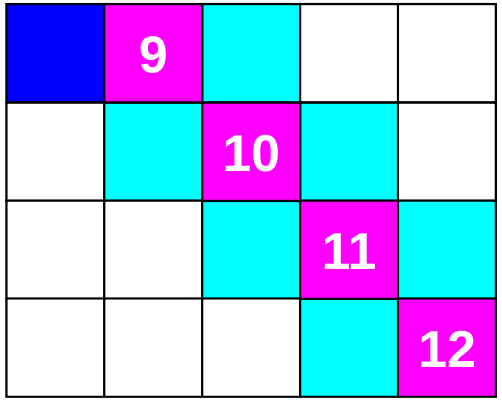
1
2
3
4



5
6
7
8

=

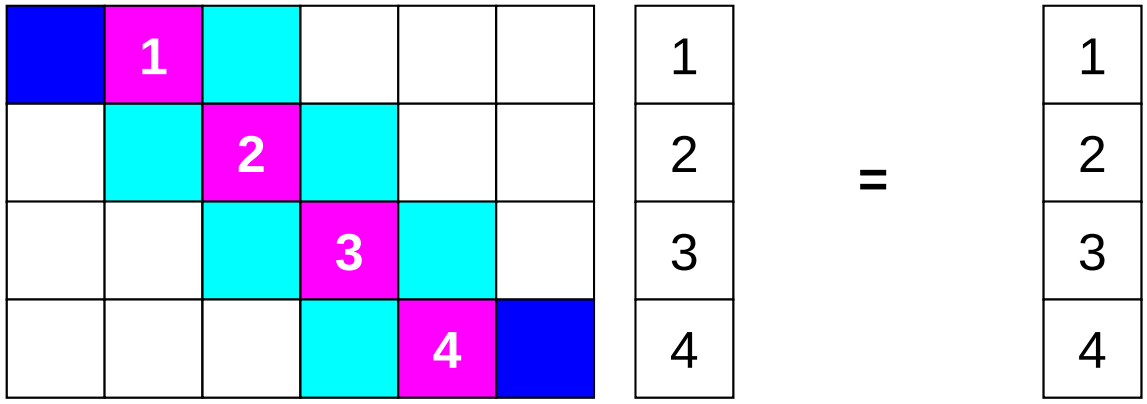
5
6
7
8

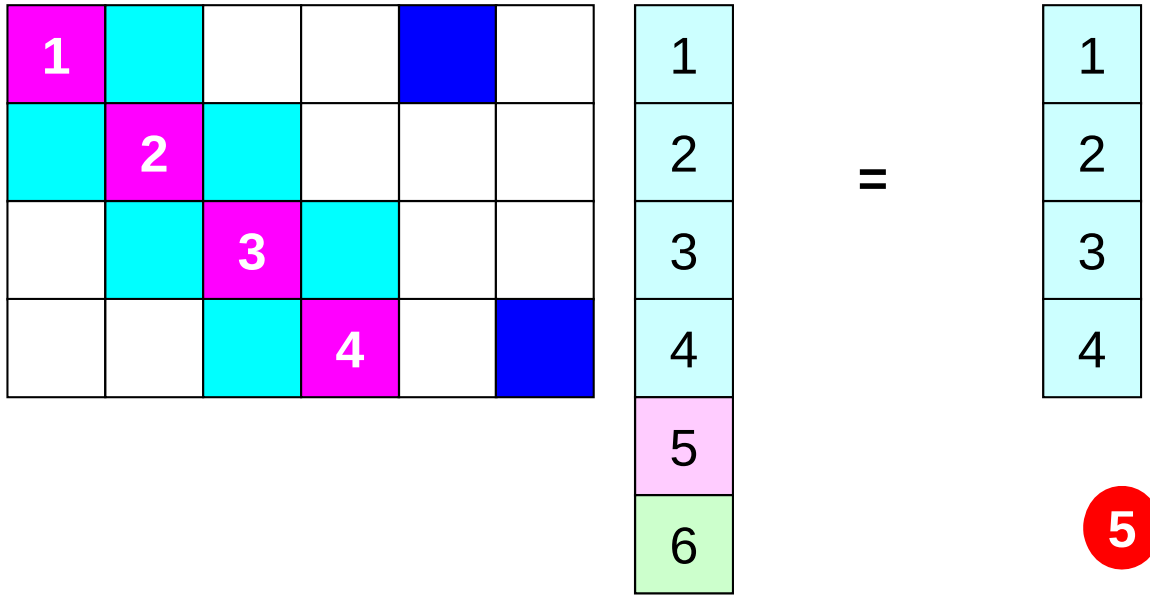


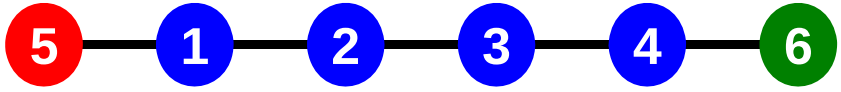
9
10
11
12

9
10
11
12

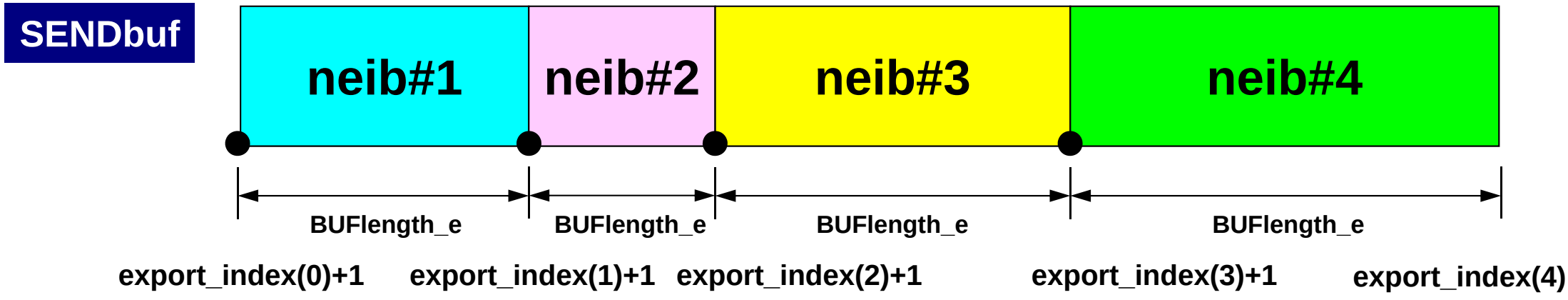
Mat-Vec Products: Local Op. #1







SEND: MPI_Isend/Irecv/Waitall



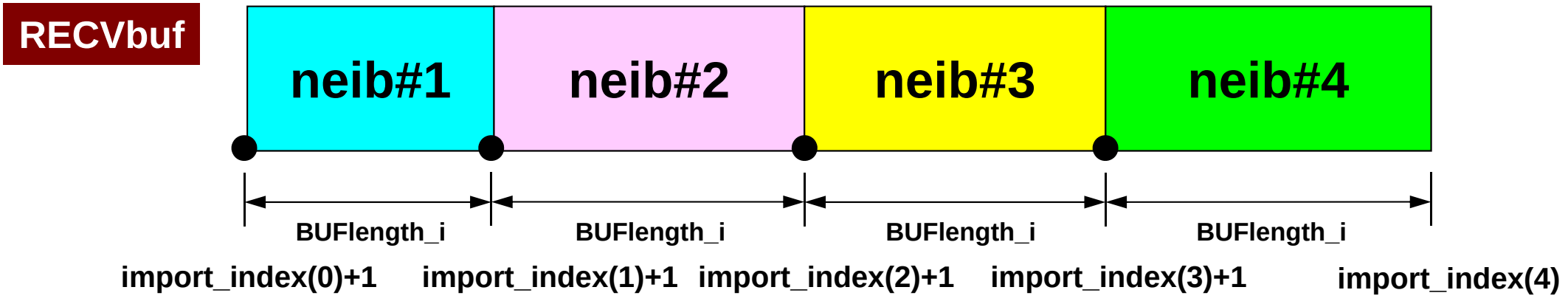

```
 do neib= 1, NEIBPETOT
   do k= export_index(neib-1)+1, export_index(neib)
     kk= export_item(k)
     SENDbuf(k)= VAL(kk)
   enddo
 enddo

 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

 call MPI_WAITALL (NEIBPETOT, request_send, stat_recv, ierr)
```

Copied to sending buffers

RECV: MPI_Isend/Irecv/Waitall

```
 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

  call MPI_WAITALL (NEIBPETOT, request_recv, stat_recv, ierr)

  do neib= 1, NEIBPETOT
     do k= import_index(neib-1)+1, import_index(neib)
       kk= import_item(k)
       VAL(kk)= RECVbuf(k)
     enddo
  enddo
```

Copied from receiving buffer



- Overview
- Distributed Local Data
- **Program**
- Results

Program: 1d.f (1/11)

Variables

```
      program heat1Dp
      implicit REAL*8 (A-H,O-Z)
      include 'mpif.h'

      integer :: N, NPLU, ITERmax
      integer :: R, Z, P, Q, DD

      real(kind=8) :: dX, RESID, EPS
      real(kind=8) :: AREA, QV, COND
      real(kind=8), dimension(:), allocatable :: PHI, RHS
      real(kind=8), dimension(:  ), allocatable :: DIAG, AMAT
      real(kind=8), dimension(:,:), allocatable :: W

      real(kind=8), dimension(2,2) :: KMAT, EMAT

      integer, dimension(:), allocatable :: ICELNOD
      integer, dimension(:), allocatable :: INDEX, ITEM
      integer(kind=4) :: NEIBPETOT, BUFlength, PETOT
      integer(kind=4), dimension(2) :: NEIBPE

      integer(kind=4), dimension(0:2) :: import_index, export_index
      integer(kind=4), dimension(  2) :: import_item , export_item

      real(kind=8), dimension(2) :: SENDbuf, RECVbuf

      integer(kind=4), dimension(:,:), allocatable :: stat_send
      integer(kind=4), dimension(:,:), allocatable :: stat_recv
      integer(kind=4), dimension(:  ), allocatable :: request_send
      integer(kind=4), dimension(:  ), allocatable :: request_recv
```

Program: 1d.f (2/11)

Control Data

```
!C
!C +-------+
!C | INIT. |
!C +-------+
!C===
!C
!C-- MPI init.

      call MPI_Init      (ierr)                                  Initialization
      call MPI_Comm_size (MPI_COMM_WORLD, PETOT, ierr )          Entire Process #: PETOT
      call MPI_Comm_rank (MPI_COMM_WORLD, my_rank, ierr )        Rank ID (0-PETot-1): my_rank

!C
!C-- CTRL data
      if (my_rank.eq.0) thenn
        open  (11, file='input.dat', status='unknown')
         read (11,*) NEg
         read (11,*) dX, QV, AREA, COND
         read (11,*) ITERmax
         read (11,*) EPS
        close (11)
      endif

      call MPI_Bcast (NEg    , 1, MPI_INTEGER, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (ITERmax, 1, MPI_INTEGER, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (dX     , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (QV     , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (AREA   , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (COND   , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (EPS    , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
```

Program: 1d.f (2/11)

Control Data

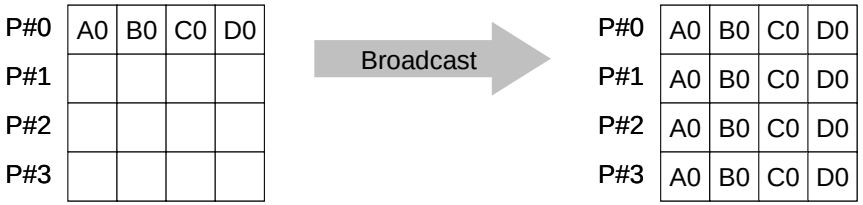
```
!C
!C +-------+
!C | INIT. |
!C +-------+
!C===
!C
!C-- MPI init.

      call MPI_Init      (ierr)                                  Initialization
      call MPI_Comm_size (MPI_COMM_WORLD, PETOT, ierr )          Entire Process #: PETOT
      call MPI_Comm_rank (MPI_COMM_WORLD, my_rank, ierr )        Rank ID (0-PETot-1): my_rank

!C
!C-- CTRL data
      if (my_rank.eq.0) then                                     Reading control file if my_rank=0
        open  (11, file='input.dat', status='unknown')
         read (11,*) Neg                                         Neg: Global Number of Elements
         read (11,*) dX, QV, AREA, COND
         read (11,*) ITERmax
         read (11,*) EPS
        close (11)
      endif

      call MPI_Bcast (NEg    , 1, MPI_INTEGER, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (ITERmax, 1, MPI_INTEGER, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (dX     , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (QV     , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (AREA   , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (COND   , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (EPS    , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
```

Program: 1d.f (2/11)

Control Data

```
!C
!C +-------+
!C | INIT. |
!C +-------+
!C===
!C
!C-- MPI init.

      call MPI_Init      (ierr)                                  Initialization
      call MPI_Comm_size (MPI_COMM_WORLD, PETOT, ierr )          Entire Process #: PETOT
      call MPI_Comm_rank (MPI_COMM_WORLD, my_rank, ierr )        Rank ID (0-PETot-1): my_rank

!C
!C-- CTRL data
      if (my_rank.eq.0) then                                     Reading control file if my_rank=0
        open  (11, file='input.dat', status='unknown')
         read (11,*) Neg                                         Neg: Global Number of Elements
         read (11,*) dX, QV, AREA, COND
         read (11,*) ITERmax
         read (11,*) EPS
        close (11)
      endif

      call MPI_Bcast (NEg    , 1, MPI_INTEGER, 0, MPI_COMM_WORLD, ierr) Parameters are sent to each proces
      call MPI_Bcast (ITERmax, 1, MPI_INTEGER, 0, MPI_COMM_WORLD, ierr) from Process #0.
      call MPI_Bcast (dX     , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (QV     , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (AREA   , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (COND   , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
      call MPI_Bcast (EPS    , 1, MPI_DOUBLE_PRECISION, 0, MPI_COMM_WORLD, ierr)
```

MPI_BCAST



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

- **`call MPI_BCAST (buffer,count,datatype,root,comm,ierr)`**
  - **`buffer`** choice I/O — starting address of buffer
    type is defined by "**`datatype`**"
  - **`count`** I I — number of elements in send/recv buffer
  - **`datatype`** I 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`** I I — rank of root process
  - **`comm`** I I — communicator
  - **`ierr`** I O — completion code

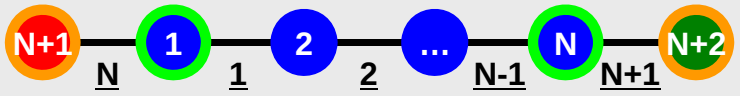
Program: 1d.f (3/11)
Distributed Local Mesh

```
!C
!C-- Local Mesh Size

      Ng= NEg + 1                          Global Number of Nodes
      N = Ng / PETOT                       Local Number of Nodes

      nr = Ng - N*PETOT                    mod(Ng,PETOT) .ne. 0
      if (my_rank.lt.nr) N= N+1

      NE= N - 1 + 2
      NP= N + 2

      if (my_rank.eq.0) NE= N - 1 + 1
      if (my_rank.eq.0) NP= N + 1

      if (my_rank.eq.PETOT-1) NE= N - 1 + 1
      if (my_rank.eq.PETOT-1) NP= N + 1

      if (PETOT.eq.1) NE= N-1
      if (PETOT.eq.1) NP= N

!C
!C- ARRAYs

      allocate (PHI(NP), DIAG(NP), AMAT(2*NP-2), RHS(NP))
      allocate (ICELNOD(2*NE))
      allocate (INDEX(0:NP), ITEM(2*NP-2), W(NP,4))
       PHI= 0.d0
      AMAT= 0.d0
      DIAG= 0.d0
       RHS= 0.d0
```

Program: 1d.f (3/11)

Distributed Local Mesh, Uniform Elements

```
!C
!C-- Local Mesh Size

      Ng= NEg + 1                          Global Number of Nodes
      N = Ng / PETOT                       Local Number of Nodes

      nr = Ng - N*PETOT                    mod(Ng,PETOT) .ne. 0
      if (my_rank.lt.nr) N= N+1

      NE= N - 1 + 2                        Number of Elements (Local)
      NP= N + 2                            Total Number of Nodes (Local) (Internal + External Nodes)

      if (my_rank.eq.0) NE= N - 1 + 1
      if (my_rank.eq.0) NP= N + 1

      if (my_rank.eq.PETOT-1) NE= N - 1 + 1
      if (my_rank.eq.PETOT-1) NP= N + 1

      if (PETOT.eq.1) NE= N-1
      if (PETOT.eq.1) NP= N
```



Others (General):
N+2 nodes
N+1 elements

```
!C
!C- ARRAYs

      allocate (PHI(NP), DIAG(NP), AMAT(2*NP-2), RHS(NP))
      allocate (ICELNOD(2*NE))
      allocate (INDEX(0:NP), ITEM(2*NP-2), W(NP,4))
       PHI= 0.d0
      AMAT= 0.d0
      DIAG= 0.d0
       RHS= 0.d0
```

Program: 1d.f (3/11)

Distributed Local Mesh, Uniform Elements

```
!C
!C-- Local Mesh Size

      Ng= NEg + 1                          Global Number of Nodes
      N = Ng / PETOT                       Local Number of Nodes

      nr = Ng - N*PETOT                    mod(Ng,PETOT) .ne. 0
      if (my_rank.lt.nr) N= N+1

      NE= N - 1 + 2                        Number of Elements (Local)
      NP= N + 2                            Total Number of Nodes (Local) (Internal + External Nodes)

      if (my_rank.eq.0) NE= N - 1 + 1
      if (my_rank.eq.0) NP= N + 1

      if (my_rank.eq.PETOT-1) NE= N - 1 + 1
      if (my_rank.eq.PETOT-1) NP= N + 1

      if (PETOT.eq.1) NE= N-1
      if (PETOT.eq.1) NP= N

!C
!C- ARRAYs

      allocate (PHI(NP), DIAG(NP), AMAT(2*NP-2), RHS(NP))
      allocate (ICELNOD(2*NE))
      allocate (INDEX(0:NP), ITEM(2*NP-2), W(NP,4))
       PHI= 0.d0
      AMAT= 0.d0
      DIAG= 0.d0
       RHS= 0.d0
```

#0:
N+1 nodes
N elements

Program: 1d.f (3/11)
Distributed Local Mesh, Uniform Elem

```
!C
!C-- Local Mesh Size

      Ng= NEg + 1                          Global Number of Nodes
      N = Ng / PETOT                       Local Number of Nodes

      nr = Ng - N*PETOT                    mod(Ng,PETOT) .ne. 0
      if (my_rank.lt.nr) N= N+1

      NE= N - 1 + 2                        Number of Elements (Local)
      NP= N + 2                            Total Number of Nodes (Local) (Internal + External Nodes)

      if (my_rank.eq.0) NE= N - 1 + 1
      if (my_rank.eq.0) NP= N + 1

      if (my_rank.eq.PETOT-1) NE= N - 1 + 1
      if (my_rank.eq.PETOT-1) NP= N + 1

      if (PETOT.eq.1) NE= N-1
      if (PETOT.eq.1) NP= N

!C
!C- ARRAYs

      allocate (PHI(NP), DIAG(NP), AMAT(2*NP-2), RHS(NP))
      allocate (ICELNOD(2*NE))
      allocate (INDEX(0:NP), ITEM(2*NP-2), W(NP,4))
       PHI= 0.d0
      AMAT= 0.d0
      DIAG= 0.d0
       RHS= 0.d0
```

#PETot-1:
N+1 nodes
N elements

Program: 1d.f (3/11)

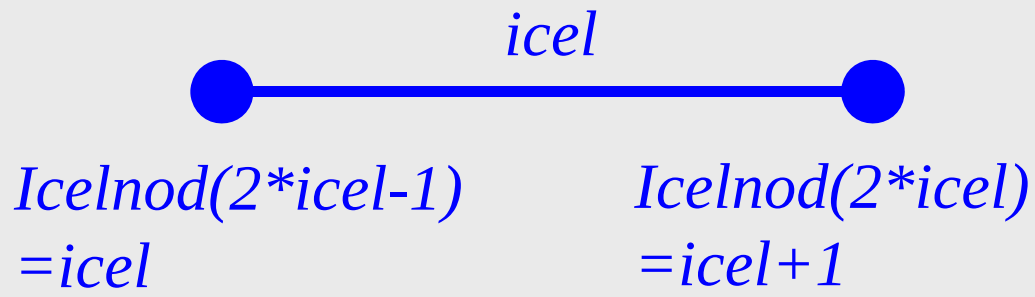
Distributed Local Mesh, Uniform Elements

```
!C
!C-- Local Mesh Size

      Ng= NEg + 1                          Global Number of Nodes
      N = Ng / PETOT                       Local Number of Nodes

      nr = Ng - N*PETOT                    mod(Ng,PETOT) .ne. 0
      if (my_rank.lt.nr) N= N+1

      NE= N - 1 + 2                        Number of Elements (Local)
      NP= N + 2                            Total Number of Nodes (Local) (Internal + External Nodes)

      if (my_rank.eq.0) NE= N - 1 + 1
      if (my_rank.eq.0) NP= N + 1

      if (my_rank.eq.PETOT-1) NE= N - 1 + 1
      if (my_rank.eq.PETOT-1) NP= N + 1

      if (PETOT.eq.1) NE= N-1
      if (PETOT.eq.1) NP= N

!C
!C- ARRAYs

      allocate (PHI(NP), DIAG(NP), AMAT(2*NP-2), RHS(NP))    Size of arrays is “NP”, not “N”
      allocate (ICELNOD(2*NE))
      allocate (INDEX(0:NP), ITEM(2*NP-2), W(NP,4))
       PHI= 0.d0
      AMAT= 0.d0
      DIAG= 0.d0
       RHS= 0.d0
```

Program: 1d.f (4/11)

Initialization of Arrays, Elements-Nodes

```
do icel= 1, NE
  ICELNOD(2*icel-1)= icel
  ICELNOD(2*icel  )= icel + 1
enddo

if (PETOT.gt.1) then

if (my_rank.eq.0) then
  icel= NE
  ICELNOD(2*icel-1)= N
  ICELNOD(2*icel  )= N + 1


 else if (my_rank.eq.PETOT-1) then
  icel= NE
  ICELNOD(2*icel-1)= N + 1
  ICELNOD(2*icel  )= 1


 else
  icel= NE - 1
  ICELNOD(2*icel-1)= N + 1
  ICELNOD(2*icel  )= 1
  icel= NE
  ICELNOD(2*icel-1)= N
  ICELNOD(2*icel  )= N + 2

endif
endif
```



Program: 1d.f (4/11)

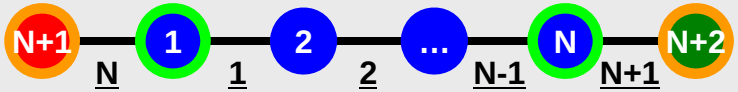
Initialization of Arrays, Elements-Nodes

```
do icel= 1, NE
  ICELNOD(2*icel-1)= icel
  ICELNOD(2*icel  )= icel + 1
enddo

if (PETOT.gt.1) then

if (my_rank.eq.0) then
  icel= NE
  ICELNOD(2*icel-1)= N
  ICELNOD(2*icel  )= N + 1


 else if (my_rank.eq.PETOT-1) then
  icel= NE
  ICELNOD(2*icel-1)= N + 1
  ICELNOD(2*icel  )= 1


 else
  icel= NE - 1
  ICELNOD(2*icel-1)= N + 1
  ICELNOD(2*icel  )= 1
  icel= NE
  ICELNOD(2*icel-1)= N
  ICELNOD(2*icel  )= N + 2

endif
endif
```

e.g. Element-1 includes node-1 and node-2

#0:
N+1 nodes
N elements

#PETot-1:
N+1 nodes
N elements



Others (General):
N+2 nodes
N+1 elements

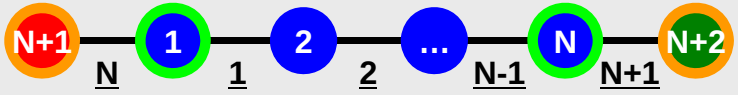
Program: 1d.f (5/11)

"Index"

```
 KMAT(1,1)= +1.d0
      KMAT(1,2)= -1.d0
      KMAT(2,1)= -1.d0
      KMAT(2,2)= +1.d0
!C===

!C
!C +-------------+
!C | CONNECTIVITY |
!C +-------------+
!C===
      INDEX   = 2

      INDEX(0)= 0

      INDEX(N+1)= 1
      INDEX(NP )= 1

      if (my_rank.eq.0)         INDEX(1)= 1
      if (my_rank.eq.PETOT-1)  INDEX(N)= 1

      do i= 1, NP
        INDEX(i)= INDEX(i) + INDEX(i-1)
      enddo

      NPLU= INDEX(NP)
      ITEM= 0
```

#0:
N+1 nodes
N elements

#PETot-1:
N+1 nodes
N elements



Others (General):
N+2 nodes
N+1 elements

Program: 1d.f (6/11)

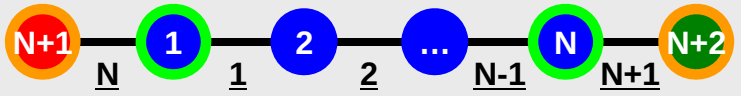
”Item”

```
do i= 1, N
  jS= INDEX(i-1)
  if (my_rank.eq.0.and.i.eq.1) then
    ITEM(jS+1)= i+1
   else if (my_rank.eq.PETOT-1.and.i.eq.N) then
    ITEM(jS+1)= i-1
   else
    ITEM(jS+1)= i-1
    ITEM(jS+2)= i+1
    if (i.eq.1) ITEM(jS+1)= N + 1
    if (i.eq.N) ITEM(jS+2)= N + 2
    if (my_rank.eq.0.and.i.eq.N) ITEM(jS+2)= N + 1
  endif
enddo
```

#0:
N+1 nodes
N elements

```
i = N + 1
jS= INDEX(i-1)
if (my_rank.eq.0) then
  ITEM(jS+1)= N
 else
  ITEM(jS+1)= 1
endif
```

#PETot-1:
N+1 nodes
N elements



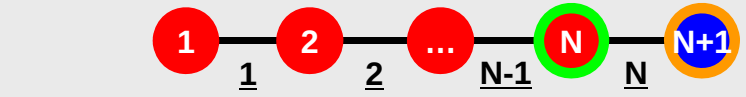
Others (General):
N+2 nodes
N+1 elements

```
i = N + 2
if (my_rank.ne.0.and.my_rank.ne.PETOT-1) then
  jS= INDEX(i-1)
  ITEM(jS+1)= N
endif
```

Program: 1d.f (7/11)

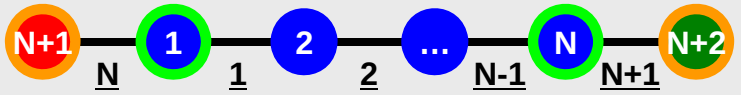
Communication Tables

```
!C
!C-- COMMUNICATION
      NEIBPETOT= 2
      if (my_rank.eq.0      ) NEIBPETOT= 1
      if (my_rank.eq.PETOT-1) NEIBPETOT= 1
      if (PETOT.eq.1)         NEIBPETOT= 0

      NEIBPE(1)= my_rank - 1
      NEIBPE(2)= my_rank + 1

      if (my_rank.eq.0      ) NEIBPE(1)= my_rank + 1
      if (my_rank.eq.PETOT-1) NEIBPE(1)= my_rank - 1

      BUFlength= 1

      import_index(1)= 1
      import_index(2)= 2
      import_item (1)= N+1
      import_item (2)= N+2

      export_index(1)= 1
      export_index(2)= 2
      export_item (1)= 1
      export_item (2)= N

      if (my_rank.eq.0) then
        import_item (1)= N+1
        export_item (1)= N
      endif
!C
!C-- INIT. arrays for MPI_Waitall
      allocate (stat_send(MPI_STATUS_SIZE,NEIBPETOT), stat_recv(MPI_STATUS_SIZE,NEIBPETOT))
      allocate (request_send(NEIBPETOT), request_recv(NEIBPETOT))
```



#0:
N+1 nodes
N elements

#PETot-1:
N+1 nodes
N elements



Others (General):
N+2 nodes
N+1 elements

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`**.

- **`call MPI_ISEND (sendbuf,count,datatype,dest,tag,comm,request, ierr)`**
  - **`sendbuf`** choice I starting address of sending buffer
  - **`count`** I I number of elements sent to each process
  - **`datatype`** I I data type of elements of sending buffer
  - **`dest`** I I rank of destination
  - **`tag`** I 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`** I I communicator
  - **`request`** I O communication request array used in `MPI_Waitall`
  - **`ierr`** I O completion code

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`**.

- **`call MPI_IRECV (recvbuf,count,datatype,dest,tag,comm,request, ierr)`**
  - **`recvbuf`** choice I starting address of receiving buffer
  - **`count`** I I number of elements in receiving buffer
  - **`datatype`** I I data type of elements of receiving buffer
  - **`source`** I I rank of source
  - **`tag`** I 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`** I I communicator
  - **`request`** I O communication request used in `MPI_Waitall`
  - **`ierr`** I O completion code

MPI_WAITALL

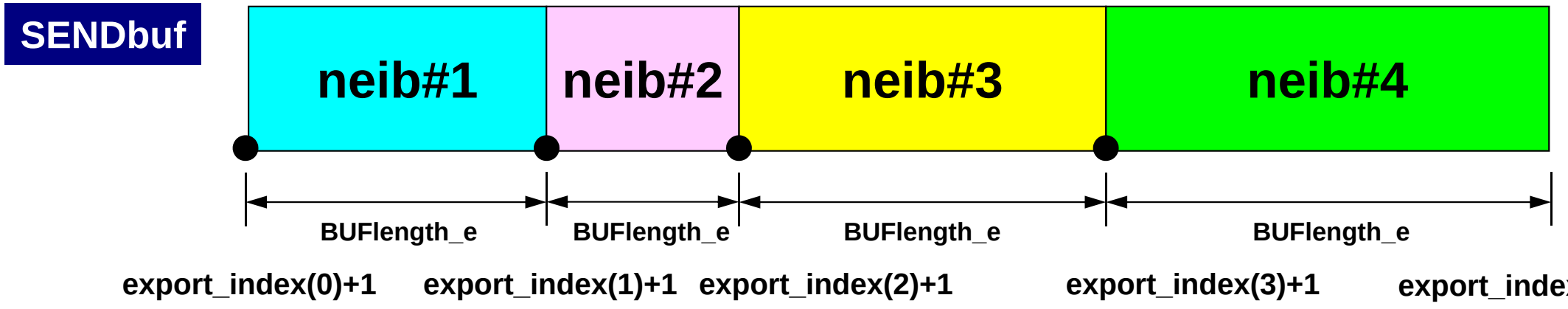
- **MPI_Waitall** blocks until all comm's, associated with **request** in the array, complete. It is used for synchronizing **MPI_Isend** and **MPI_Irecv** in this class.
- At sending phase, contents of sending buffer cannot be modified before calling corresponding **MPI_Waitall**. At receiving phase, 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.

- **call MPI_WAITALL (count,request,status,ierr)**
  - **count** I I number of processes to be synchronized
  - **request** I I/O comm. request used in MPI_Waitall (array size: count)
  - **status** I O array of status objects
    MPI_STATUS_SIZE: defined in 'mpif.h', 'mpi.h'
  - **ierr** I O completion code

Generalized Comm. Table: Send

- Neighbors
  - NEIBPETOT, NEIBPE(neib)
- Message size for each neighbor
  - export_index(neib), neib= 0, NEIBPETOT
- ID of **boundary** points
  - export_item(k), k= 1, export_index(NEIBPETOT)
- Messages to each neighbor
  - SENDbuf(k), k= 1, export_index(NEIBPETOT)

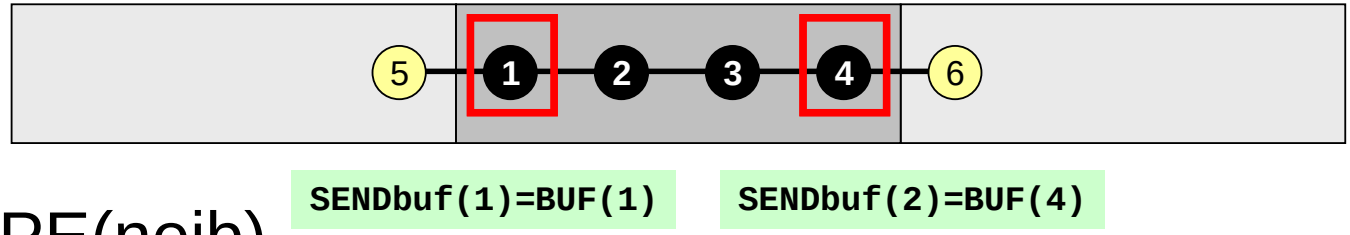
SEND: MPI_Isend/Irecv/Waitall




```
 do neib= 1, NEIBPETOT
   do k= export_index(neib-1)+1, export_index(neib)
     kk= export_item(k)
     SENDbuf(k)= VAL(kk)
   enddo
 enddo

 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

 call MPI_WAITALL (NEIBPETOT, request_send, stat_recv, ierr)
```

Copied to sending buffers

SEND/Export: 1D Problem



- Neighbors
  - NEIBPETOT, NEIBPE(neib)
    - NEIBPETOT=2, NEIB(1)= my_rank-1, NEIB(2)= my_rank+1
- Message size for each neighbor
  - export_index(neib), neib= 0, NEIBPETOT
    - export_index(0)=0, export_index(1)= 1, export_index(2)= 2
- ID of **boundary** points
  - export_item(k), k= 1, export_index(NEIBPETOT)
    - export_item(1)= 1, export_item(2)= N
- Messages to each neighbor
  - SENDbuf(k), k= 1, export_index(NEIBPETOT)
    - SENDbuf(1)= BUF(1), SENDbuf(2)= BUF(N)

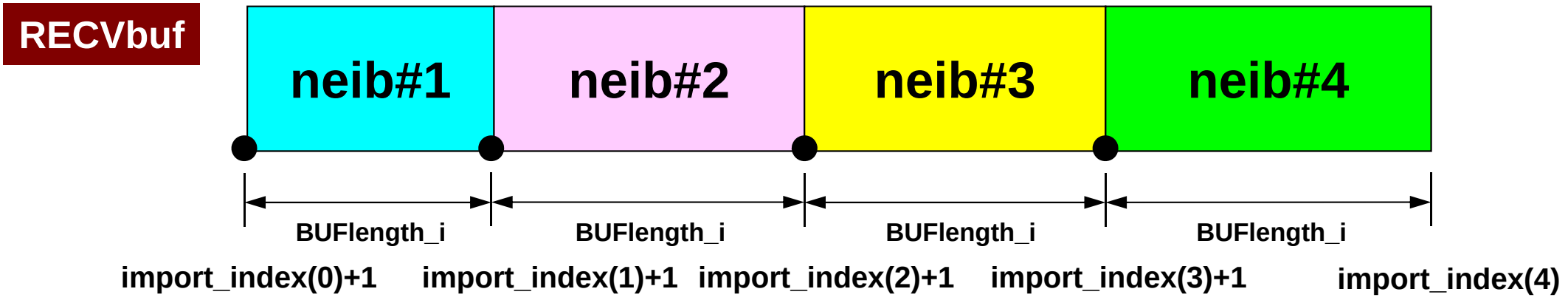
Generalized Comm. Table: Receive

- Neighbors
  - NEIBPETOT, NEIBPE(neib)
- Message size for each neighbor
  - import_index(neib), neib= 0, NEIBPETOT
- ID of **external** points
  - import_item(k), k= 1, import_index(NEIBPETOT)
- Messages from each neighbor
  - RECVbuf(k), k= 1, import_index(NEIBPETOT)

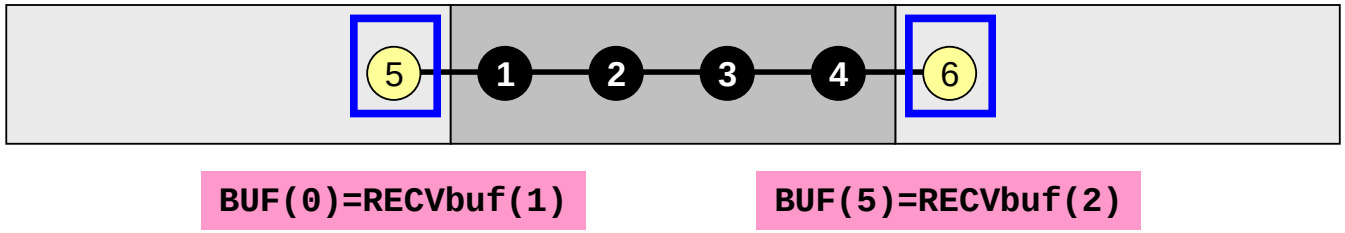
RECV: MPI_Isend/Irecv/Waitall

```
 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

  call MPI_WAITALL (NEIBPETOT, request_recv, stat_recv, ierr)

  do neib= 1, NEIBPETOT
     do k= import_index(neib-1)+1, import_index(neib)
       kk= import_item(k)
       VAL(kk)= RECVbuf(k)
     enddo
  enddo
```

Copied from receiving buffer

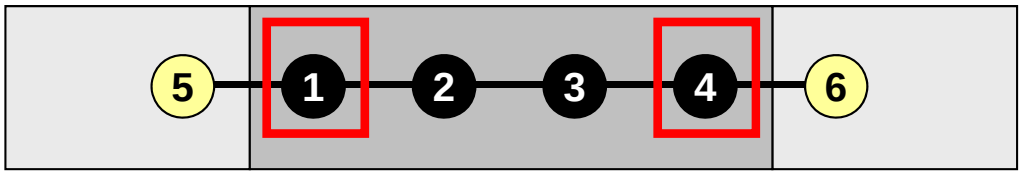


RECV/Import: 1D Proble



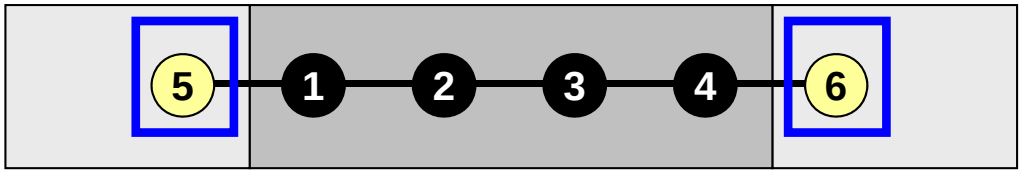
- Neighbors
  - NEIBPETOT, NEIBPE(neib)
    - NEIBPETOT=2, NEIB(1)= my_rank-1, NEIB(2)= my_rank+1
- Message size for each neighbor
  - import_index(neib), neib= 0, NEIBPETOT
    - import_index(0)=0, import_index(1)= 1, import_index(2)= 2
- ID of **external** points
  - import_item(k), k= 1, import_index(NEIBPETOT)
    - import_item(1)= N+1, import_item(2)= N+2
- Messages from each neighbor
  - RECVbuf(k), k= 1, import_index(NEIBPETOT)
    - BUF(N+1)=RECVbuf(1), BUF(N+2)=RECVbuf(2)

Generalized Comm. Table: Fortran



SENDbuf(1)=BUF(1)

SENDbuf(2)=BUF(4)

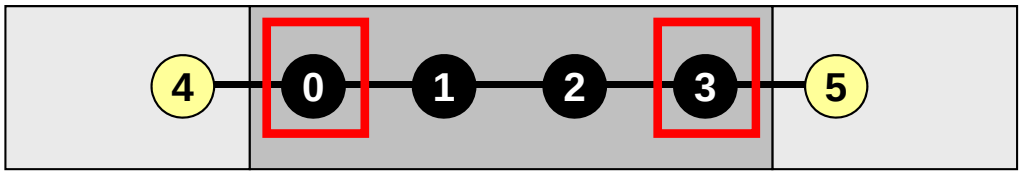


BUF(5)=RECVbuf(1)

BUF(6)=RECVbuf(2)

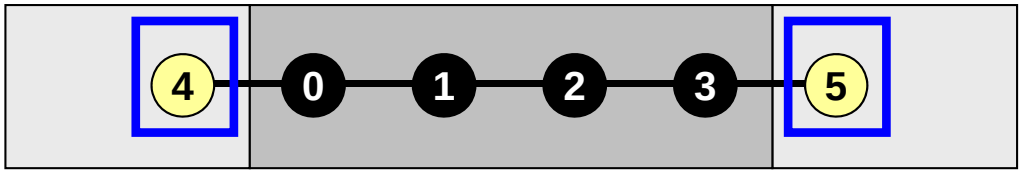
```
NEIBPETOT= 2
NEIBPE(1)= my_rank - 1
NEIBPE(2)= my_rank + 1

import_index(1)= 1
import_index(2)= 2
import_item (1)= N+1
import_item (2)= N+2

export_index(1)= 1
export_index(2)= 2
export_item (1)= 1
export_item (2)= N

if (my_rank.eq.0) then
  import_item (1)= N+1
  export_item (1)= N
  NEIBPE(1)= my_rank+1
endif
```

Generalized Comm. Table: C



SENDbuf[0]=BUF[0]

SENDbuf[1]=BUF[3]



BUF[4]=RECVbuf[0]

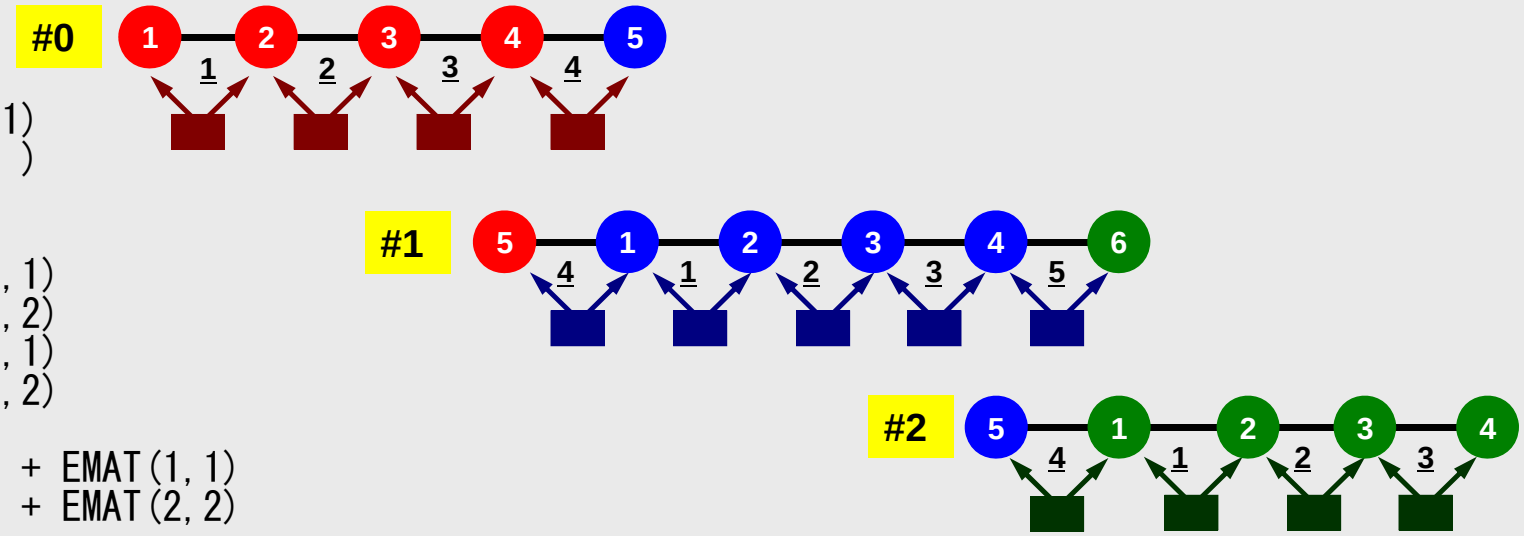
BUF[5]=RECVbuf[1]

```
NEIBPETOT= 2
NEIBPE[0]= my_rank - 1
NEIBPE[1]= my_rank + 1

import_index[1]= 0
import_index[2]= 1
import_item [0]= N
import_item [1]= N+1

export_index[1]= 0
export_index[2]= 1
export_item [0]= 0
export_item [1]= N-1

if (my_rank.eq.0) then
  import_item [0]= N
  export_item [0]= N-1
  NEIBPE[0]= my_rank+1
endif
```

Program: 1d.f (8/11)

Matrix Assembling, NO changes from 1-CPU co

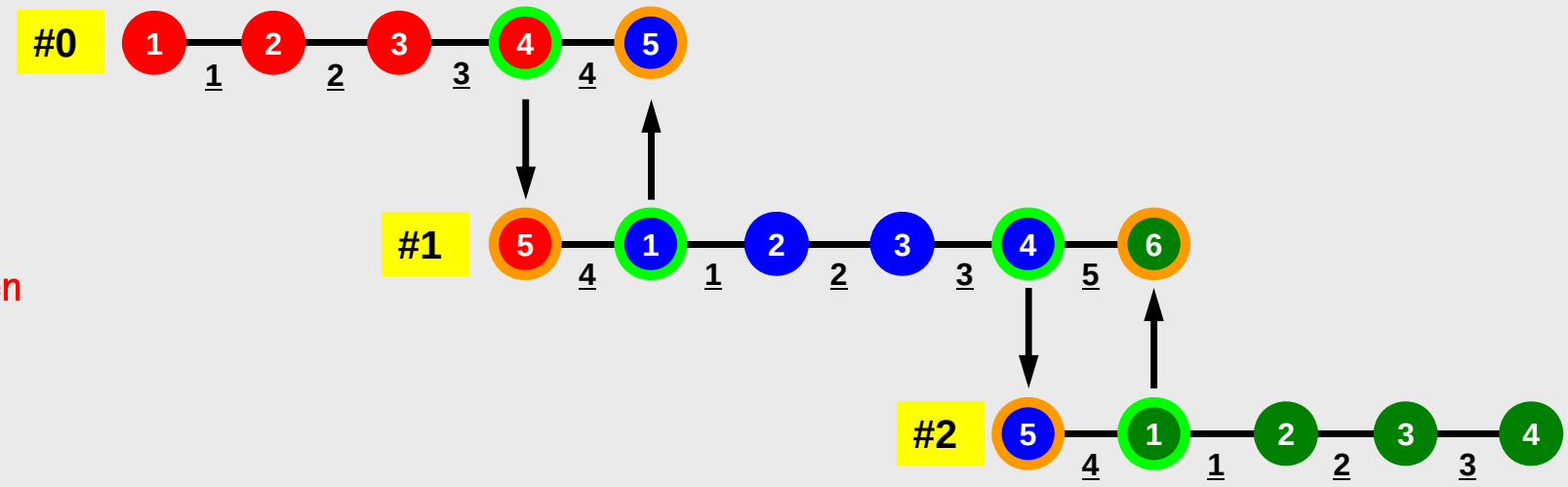
```
!C
!C +----------------+
!C | MATRIX ASSEMBLE |
!C +----------------+
!C===
      do icel= 1, NE
        in1= ICELNOD(2*icel-1)
        in2= ICELNOD(2*icel  )
        DL = dX
        cK= AREA*COND/DL
        EMAT(1,1)= Ck*KMAT(1,1)
        EMAT(1,2)= Ck*KMAT(1,2)
        EMAT(2,1)= Ck*KMAT(2,1)
        EMAT(2,2)= Ck*KMAT(2,2)

        DIAG(in1)= DIAG(in1) + EMAT(1,1)
        DIAG(in2)= DIAG(in2) + EMAT(2,2)

        if (my_rank.eq.0.and.icel.eq.1) then
          k1= INDEX(in1-1) + 1
         else
          k1= INDEX(in1-1) + 2
        endif
        k2= INDEX(in2-1) + 1

        AMAT(k1)= AMAT(k1) + EMAT(1,2)
        AMAT(k2)= AMAT(k2) + EMAT(2,1)

        QN= 0.50d0*QV*AREA*DL
        RHS(in1)= RHS(in1) + QN
        RHS(in2)= RHS(in2) + QN
      enddo
!C===
```



Program: 1d.f (9/11)

Boundary Cond., ALMOST NO changes from 1-CPU code

```
!C
!C +--------------------+
!C | BOUNDARY CONDITIONS |
!C +--------------------+
!C===

!C
!C-- X=Xmin

      if (my_rank.eq.0) then
        i = 1
        jS= INDEX(i-1)

        AMAT(jS+1)= 0.d0
        DIAG(i)= 1.d0
        RHS (i)= 0.d0
        do k= 1, NPLU
          if (ITEM(k).eq.1) AMAT(k)= 0.d0
        enddo
      endif

!C===
```



Program: 1d.c（10/11）

Conjugate Gradient Method

```
!C
!C +--------------+
!C | CG iterations |
!C +--------------+
!C===
      R = 1
      Z = 2
      Q = 2
      P = 3
      DD= 4

      do i= 1, N
        W(i,DD)= 1.0D0 / DIAG(i)
      enddo

!C
!C-- {r0}= {b} - [A]{xini} |

!C-    init

       do neib= 1, NEIBPETOT
         do k= export_index(neib-1)+1, export_index(neib)
           kk= export_item(k)
           SENDbuf(k)= PHI(kk)
         enddo
       enddo
```

Compute $r^{(0)}= b-[A]x^{(0)}$
for i= 1, 2, …
  solve $[M]z^{(i-1)}= r^{(i-1)}$
  $\rho_{i-1}= r^{(i-1)}\ z^{(i-1)}$
  if i=1
    $p^{(1)}= z^{(0)}$
  else
    $\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
    $p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
  endif
  $q^{(i)}= [A]p^{(i)}$
  $\alpha_i\ = \rho_{i-1}/p^{(i)}q^{(i)}$
  $x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$
  $r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$
  check convergence |r|
end

Conjugate Gradient Method (CG

- Matrix-Vector Multiply
- Dot Product
- Preconditioning: in the same way as 1CPU code
- DAXPY: in the same way as 1CPU code

Preconditioning, DAXPY

```
!C
!C-- {z}= [Minv]{r}

      do i= 1, N
        W(i,Z)= W(i,DD) * W(i,R)
      enddo
```

```
!C
!C-- {x}= {x} + ALPHA*{p}
!C   {r}= {r} - ALPHA*{q}

      do i= 1, N
        PHI(i)= PHI(i) + ALPHA * W(i,P)
        W(i,R)= W(i,R) - ALPHA * W(i,Q)
      enddo
```

Matrix-Vector Multiply (1/2)

Using Comm. Table, {p} is updated before computation

```
!C
!C-- {q}= [A]{p}

      do neib= 1, NEIBPETOT
        do k= export_index(neib-1)+1, export_index(neib)
          kk= export_item(k)
          SENDbuf(k)= W(kk,P)
        enddo
      enddo

      do neib= 1, NEIBPETOT
        is   = export_index(neib-1) + 1
        len_s= export_index(neib) - export_index(neib-1)
        call MPI_Isend (SENDbuf(is), len_s, MPI_DOUBLE_PRECISION,        &
     &                  NEIBPE(neib), 0, MPI_COMM_WORLD, request_send(neib), ierr)
      enddo

      do neib= 1, NEIBPETOT
        ir   = import_index(neib-1) + 1
        len_r= import_index(neib) - import_index(neib-1)
        call MPI_Irecv (RECVbuf(ir), len_r, MPI_DOUBLE_PRECISION,        &
     &                  NEIBPE(neib), 0, MPI_COMM_WORLD, request_recv(neib), ierr)
      enddo

      call MPI_Waitall (NEIBPETOT, request_recv, stat_recv, ierr)

      do neib= 1, NEIBPETOT
        do k= import_index(neib-1)+1, import_index(neib)
          kk= import_item(k)
          W(kk,P)= RECVbuf(k)
        enddo
      enddo
```

Matrix-Vector Multiply (2/2)

{q}= [A]{p}

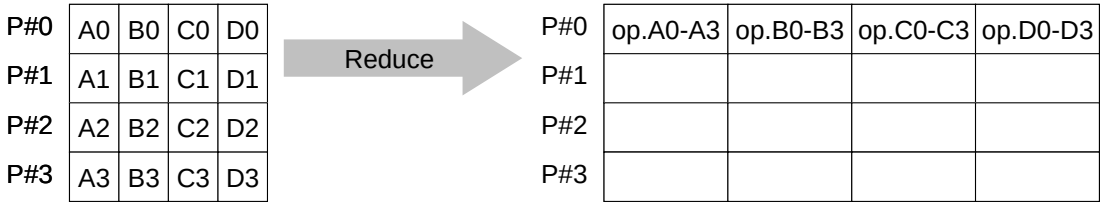
```
call MPI_Waitall (NEIBPETOT, request_send, stat_send, ierr)

do i= 1, N
  W(i,Q) = DIAG(i)*W(i,P)
  do j= INDEX(i-1)+1, INDEX(i)
    W(i,Q) = W(i,Q) + AMAT(j)*W(ITEM(j),P)
  enddo
enddo
```

Dot Product

Global Summation by MPI_Allreduce

```
!C
!C-- RHO= {r}{z}

      RHO0= 0.d0
      do i= 1, N
        RHO0= RHO0 + W(i,R)*W(i,Z)
      enddo
      call MPI_Allreduce (RHO0, RHO, 1, MPI_DOUBLE_PRECISION,          &
     &                    MPI_SUM, MPI_COMM_WORLD, ierr)
```

MPI_REDUCE



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

- **`call MPI_REDUCE (sendbuf,recvbuf,count,datatype,op,root,comm,ierr)`**
  - **`sendbuf`** choice I starting address of send buffer
  - **`recvbuf`** choice O starting address receive buffer
    type is defined by "**`datatype`**"
  - **`count`** I I number of elements in send/receive buffer
  - **`datatype`** I 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`** I 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`** I I rank of root process
  - **`comm`** I I communicator
  - **`ierr`** I O completion code

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.

Example of MPI_Reduce (1/2)

```
call MPI_REDUCE
(sendbuf,recvbuf,count,datatype,op,root,comm,ierr)
```

```
real(kind=8):: X0, X1

call MPI_REDUCE
(X0, X1, 1, MPI_DOUBLE_PRECISION, MPI_MAX, 0, <comm>, ierr)
```

```
real(kind=8):: X0(4), XMAX(4)

call MPI_REDUCE
(X0, XMAX, 4, MPI_DOUBLE_PRECISION, MPI_MAX, 0, <comm>, ierr)
```

Global Max values of X0(i) go to XMAX(i) on #0 process（i=1~4）

Example of MPI_Reduce (2/2)

```
call MPI_REDUCE
(sendbuf,recvbuf,count,datatype,op,root,comm,ierr)
```

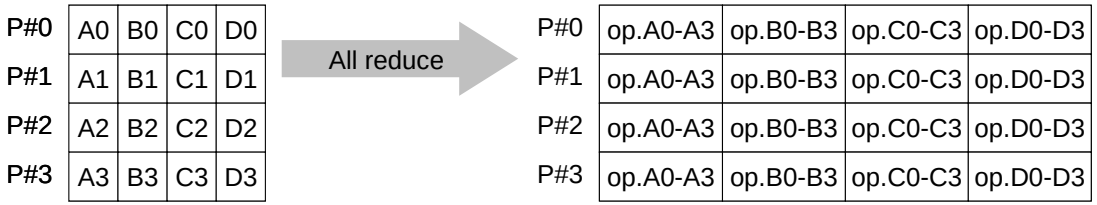
```
real(kind=8):: X0, XSUM

call MPI_REDUCE
(X0, XSUM, 1, MPI_DOUBLE_PRECISION, MPI_SUM, 0, <comm>, ierr)
```

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

```
real(kind=8):: X0(4)

call MPI_REDUCE
(X0(1), X0(3), 2, MPI_DOUBLE_PRECISION, MPI_SUM, 0, <comm>, ierr)
```

- Global summation of X0(1) goes to X0(3) on #0 process.
- Global summation of X0(2) goes to X0(4) on #0 process.

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,ierr)`**
  - **`sendbuf`** choice I — starting address of send buffer
  - **`recvbuf`** choice O — starting address receive buffer
    type is defined by **"`datatype`"**
  - **`count`** I I — number of elements in send/recv buffer
  - **`datatype`** I I — data type of elements in send/recv buffer
  - **`op`** I I — reduce operation
  - **`comm`** I I — commuinicator
  - **`ierr`** I O — completion code

CG method (1/5)

```
!C
!C-- {r0}= {b} - [A]{xini}
    do neib= 1, NEIBPETOT
      do k= export_index(neib-1)+1, export_index(neib)
        kk= export_item(k)
        SENDbuf(k)= PHI(kk)
      enddo
    enddo

    do neib= 1, NEIBPETOT
      is   = export_index(neib-1) + 1
      len_s= export_index(neib) - export_index(neib-1)
      call MPI_Isend (SENDbuf(is), len_s,
     &                MPI_DOUBLE_PRECISION,
     &                NEIBPE(neib), 0, MPI_COMM_WORLD,
     &                request_send(neib), ierr)
    enddo

    do neib= 1, NEIBPETOT
      ir   = import_index(neib-1) + 1
      len_r= import_index(neib) - import_index(neib-1)
      call MPI_Irecv (RECVbuf(ir), len_r,
     &                MPI_DOUBLE_PRECISION,
     &                NEIBPE(neib), 0, MPI_COMM_WORLD,
     &                request_recv(neib), ierr)
    enddo
    call MPI_Waitall (NEIBPETOT, request_recv, stat_recv, ier

    do neib= 1, NEIBPETOT
      do k= import_index(neib-1)+1, import_index(neib)
        kk= import_item(k)
        PHI(kk)= RECVbuf(k)
      enddo
    enddo
    call MPI_Waitall (NEIBPETOT, request_send, stat_send, ierr)
```

Compute $r^{(0)}= b-[A]x^{(0)}$
for i= 1, 2, …
  solve $[M]z^{(i-1)}= r^{(i-1)}$
  $\rho_{i-1}= r^{(i-1)}\ z^{(i-1)}$
  if i=1
    $p^{(1)}= z^{(0)}$
  else
    $\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
    $p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
  endif
  $q^{(i)}= [A]p^{(i)}$
  $\alpha_i\ = \rho_{i-1}/p^{(i)}q^{(i)}$
  $x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$
  $r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$
  check convergence |r|
end

CG method (2/5)

```
      do i= 1, N
        W(i,R) = DIAG(i)*PHI(i)
        do j= INDEX(i-1)+1, INDEX(i)
          W(i,R) = W(i,R) + AMAT(j)*PHI(ITEM(j))
        enddo
      enddo

      BNRM20= 0.0D0
      do i= 1, N
        BNRM20 = BNRM20  + RHS(i)  **2
        W(i,R) = RHS(i) - W(i,R)
      enddo
      call MPI_Allreduce (BNRM20, BNRM2, 1,
     &                    MPI_DOUBLE_PRECISION,
     &                    MPI_SUM, MPI_COMM_WORLD, ierr)

!C***********************************************************
      do iter= 1, ITERmax

!C
!C-- {z}= [Minv]{r}

      do i= 1, N
        W(i,Z)= W(i,DD) * W(i,R)
      enddo
!C
!C-- RHO= {r}{z}

      RHO0= 0.d0
      do i= 1, N
        RHO0= RHO0 + W(i,R)*W(i,Z)
      enddo
      call MPI_Allreduce (RHO0, RHO, 1, MPI_DOUBLE_PRECISION,
     &                    MPI_SUM, MPI_COMM_WORLD, ierr)
```

Compute $r^{(0)}= b-[A]x^{(0)}$
for i= 1, 2, …
solve $[M]z^{(i-1)}= r^{(i-1)}$
$\rho_{i-1}= r^{(i-1)}\ z^{(i-1)}$
if i=1
$p^{(1)}= z^{(0)}$
else
$\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
$p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
endif
$q^{(i)}= [A]p^{(i)}$
$\alpha_i = \rho_{i-1}/p^{(i)}q^{(i)}$
$x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$
$r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$
check convergence |r|
end

CG method (3/5)

```
!C
!C-- {p} = {z} if      ITER=1
!C   BETA= RHO / RHO1  otherwise

      if ( iter.eq.1 ) then
        do i= 1, N
          W(i,P)= W(i,Z)
        enddo
       else
        BETA= RHO / RHO1
        do i= 1, N
          W(i,P)= W(i,Z) + BETA*W(i,P)
        enddo
      endif


!C
!C-- {q}= [A]{p}

      do neib= 1, NEIBPETOT
        do k= export_index(neib-1)+1, export_index(neib)
          kk= export_item(k)
          SENDbuf(k)= W(kk,P)
        enddo
      enddo

      do neib= 1, NEIBPETOT
        is   = export_index(neib-1) + 1
        len_s= export_index(neib) - export_index(neib-1)
        call MPI_Isend (SENDbuf(is), len_s, MPI_DOUBLE_PRECISION,       &
     &                  NEIBPE(neib), 0, MPI_COMM_WORLD,                &
     &                  request_send(neib), ierr)
      enddo
```

Compute $r^{(0)}= b-[A]x^{(0)}$
for **i= 1, 2, …**
  solve $[M]z^{(i-1)}= r^{(i-1)}$
  $\rho_{i-1}= r^{(i-1)}\ z^{(i-1)}$
  if i=1
    $p^{(1)}= z^{(0)}$
  else
    $\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
    $p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
  endif
  $q^{(i)}= [A]p^{(i)}$
  $\alpha_i\ = \rho_{i-1}/p^{(i)}q^{(i)}$
  $x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$
  $r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$
  check convergence |r|
end

CG method (4/5)

```
  do neib= 1, NEIBPETOT
    ir   = import_index(neib-1) + 1
    len_r= import_index(neib) - import_index(neib-1)
    call MPI_Irecv (RECVbuf(ir), len_r,
&                   MPI_DOUBLE_PRECISION,
&                   NEIBPE(neib), 0, MPI_COMM_WORLD,
&                   request_recv(neib), ierr)
  enddo
  call MPI_Waitall (NEIBPETOT, request_recv, stat_recv, ierr)

  do neib= 1, NEIBPETOT
    do k= import_index(neib-1)+1, import_index(neib)
      kk= import_item(k)
      W(kk,P)= RECVbuf(kk)
    enddo
  enddo
  call MPI_Waitall (NEIBPETOT, request_send, stat_send, ierr)

  do i= 1, N
    W(i,Q) = DIAG(i)*W(i,P)
    do j= INDEX(i-1)+1, INDEX(i)
      W(i,Q) = W(i,Q) + AMAT(j)*W(ITEM(j),P)
    enddo
  enddo

!C
!C-- ALPHA= RHO / {p}{q}

  C10= 0.d0
  do i= 1, N
    C10= C10 + W(i,P)*W(i,Q)
  enddo
  call MPI_Allreduce (C10, C1, 1, MPI_DOUBLE_PRECISION, MPI_SUM, MPI_COMM_WORLD, ierr)
  ALPHA= RHO / C1
```

Compute $r^{(0)}= b-[A]x^{(0)}$
for i= 1, 2, …
  solve $[M]z^{(i-1)}= r^{(i-1)}$
  $\rho_{i-1}= r^{(i-1)}\ z^{(i-1)}$
  if i=1
    $p^{(1)}= z^{(0)}$
  else
    $\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
    $p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
  endif
  $q^{(i)}= [A]p^{(i)}$
  $\alpha_i = \rho_{i-1}/p^{(i)}q^{(i)}$
  $x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$
  $r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$
  check convergence |r|
end

CG method (5/5)

```
!C
!C-- {x}= {x} + ALPHA*{p}
!C   {r}= {r} - ALPHA*{q}

      do i= 1, N
        PHI(i)= PHI(i) + ALPHA * W(i,P)
        W(i,R)= W(i,R) - ALPHA * W(i,Q)
      enddo

      DNRM20 = 0.0
      do i= 1, N
        DNRM20= DNRM20 + W(i,R)**2
      enddo

      call MPI_Allreduce (DNRM20, DNRM2, 1,
     &                    MPI_DOUBLE_PRECISION,
     &                    MPI_SUM, MPI_COMM_WORLD, ierr)

        RESID= dsqrt(DNRM2/BNRM2)

        if (my_rank.eq.0.and.mod(iter,1000).eq.0) then
          write (*, '(i8,1pe16.6)') iter, RESID
        endif

        if ( RESID.le.EPS) goto 900
        RHO1 = RHO

      enddo
```

Compute $r^{(0)}= b-[A]x^{(0)}$

for i= 1, 2, …

- solve $[M]z^{(i-1)}= r^{(i-1)}$
- $\rho_{i-1}= r^{(i-1)}\ z^{(i-1)}$
- if i=1
  - $p^{(1)}= z^{(0)}$
- else
  - $\beta_{i-1}= \rho_{i-1}/\rho_{i-2}$
  - $p^{(i)}= z^{(i-1)} + \beta_{i-1}\ p^{(i-1)}$
- endif
- $q^{(i)}= [A]p^{(i)}$
- $\alpha_i\ = \rho_{i-1}/p^{(i)}q^{(i)}$
- **$x^{(i)}= x^{(i-1)} + \alpha_i p^{(i)}$**
- **$r^{(i)}= r^{(i-1)} - \alpha_i q^{(i)}$**
- **check convergence |r|**

end

Program: 1d.f (11/11)

Output by Each Proces

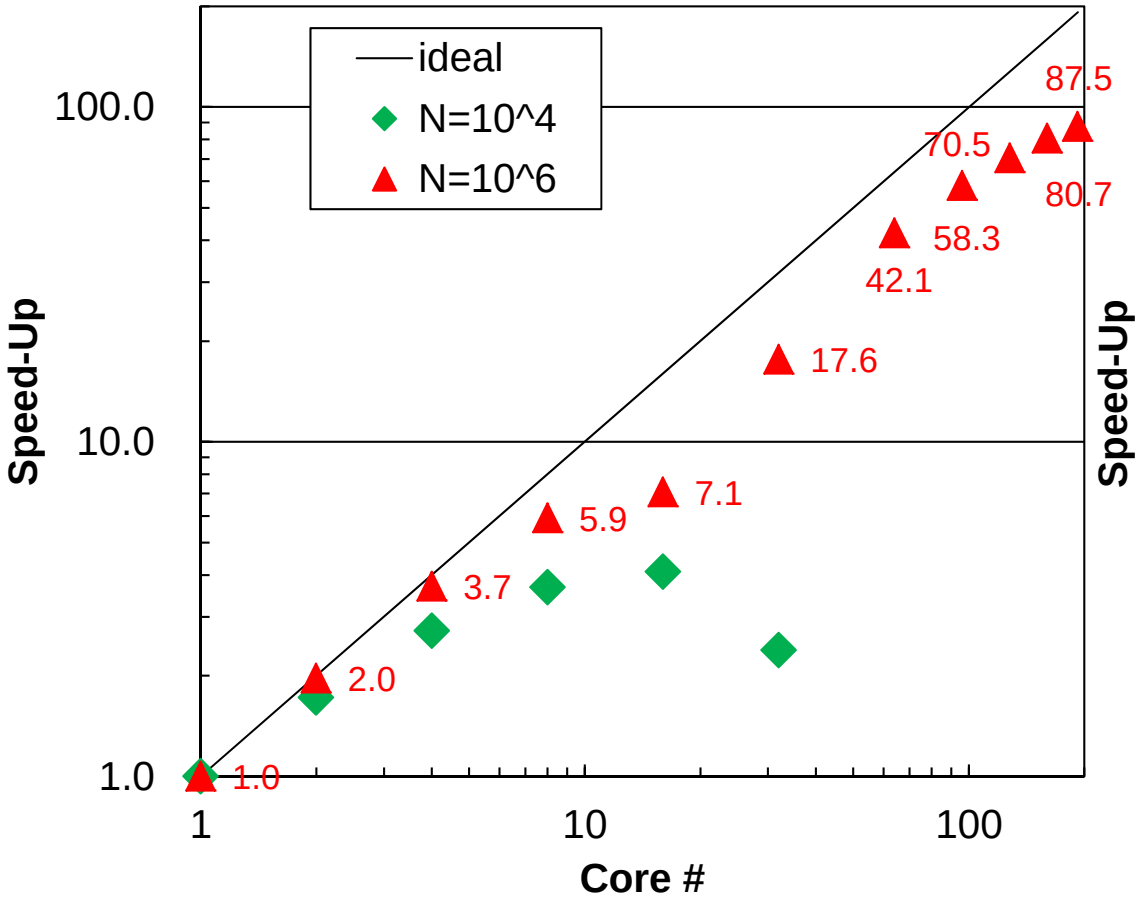
```
!C
!C-- OUTPUT
        if (my_rank.eq.0) then
          write (*,'(2(1pe16.6))') E1Time-S1Time, E2Time-E1Time
        endif

      write (*,'(/a)') '### TEMPERATURE'
      do i= 1, N
        write (*,'(2i8, 2(1pe16.6))') my_rank, i, PHI(i)
      enddo

      call MPI_FINALIZE (ierr)
      end program heat1Dp
```

- Overview
- Distributed Local Data
- Program
- **Results**

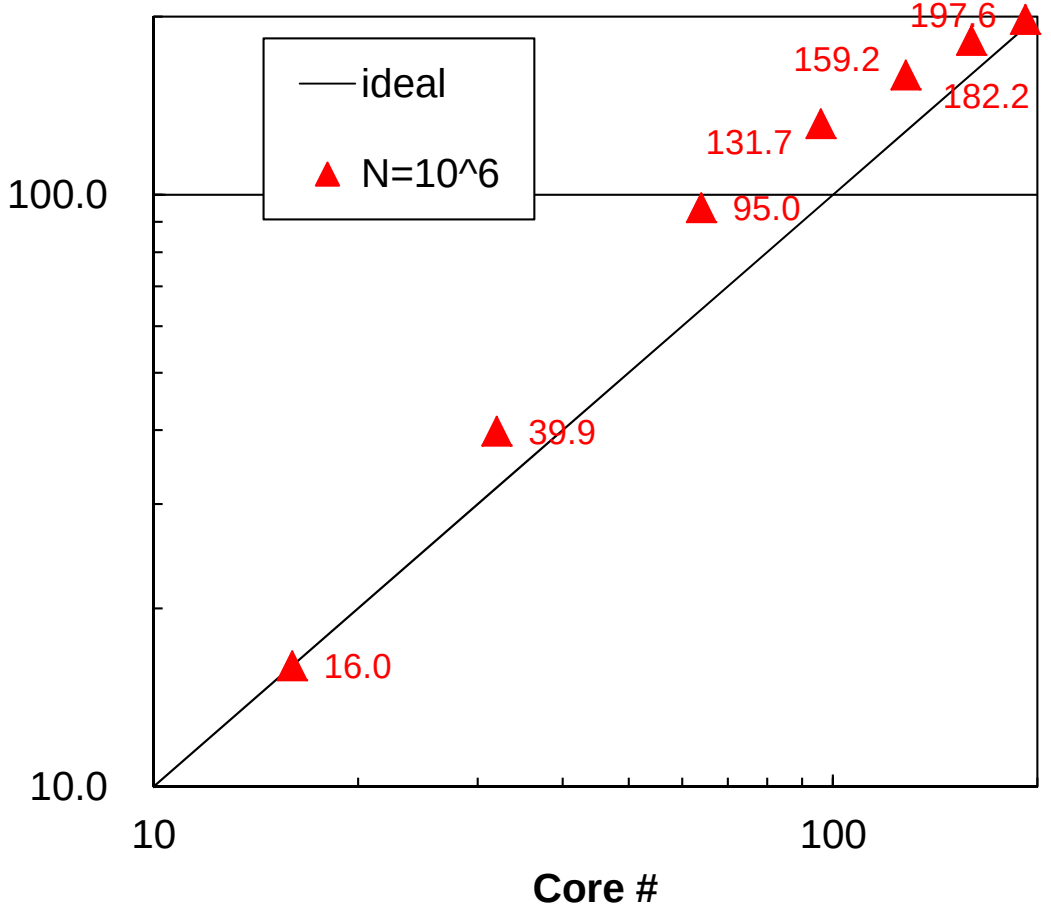
Results for CG Solver

Time for 100 Iterations in $N=10^6$ case

based on a core



based on a node (16 cores)



Performance is lower than ideal one

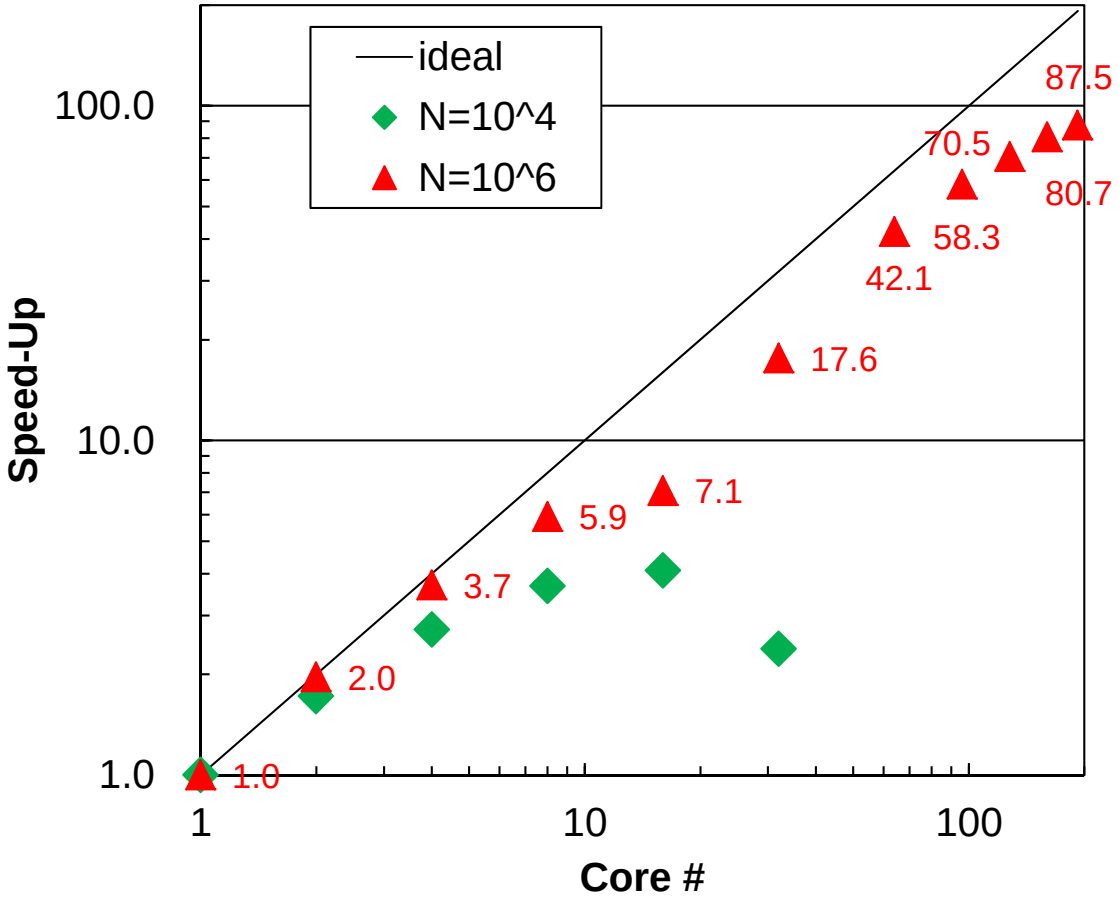
- Time for MPI communication
  - Time for sending data
  - Communication bandwidth between nodes
  - Time is proportional to size of sending/receiving buffers
- Time for starting MPI
  - latency
  - does not depend on size of buffers
    - depends on number of calling, increases according to process #
  - $O(10^0)$-$O(10^1)$ μsec.
- Synchronization of MPI
  - Increases according to number of processes

Performance is lower than ideal one (cont.)

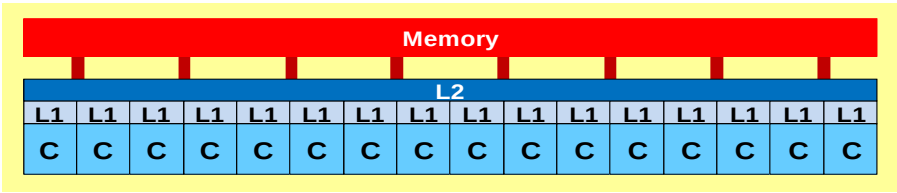
- If computation time is relatively small (N is small in S1-3), these effects are not negligible.
  - If the size of messages is small, effect of “latency” is significant.

Performance is not so good... between 1-16 cores

based on performance at a single core



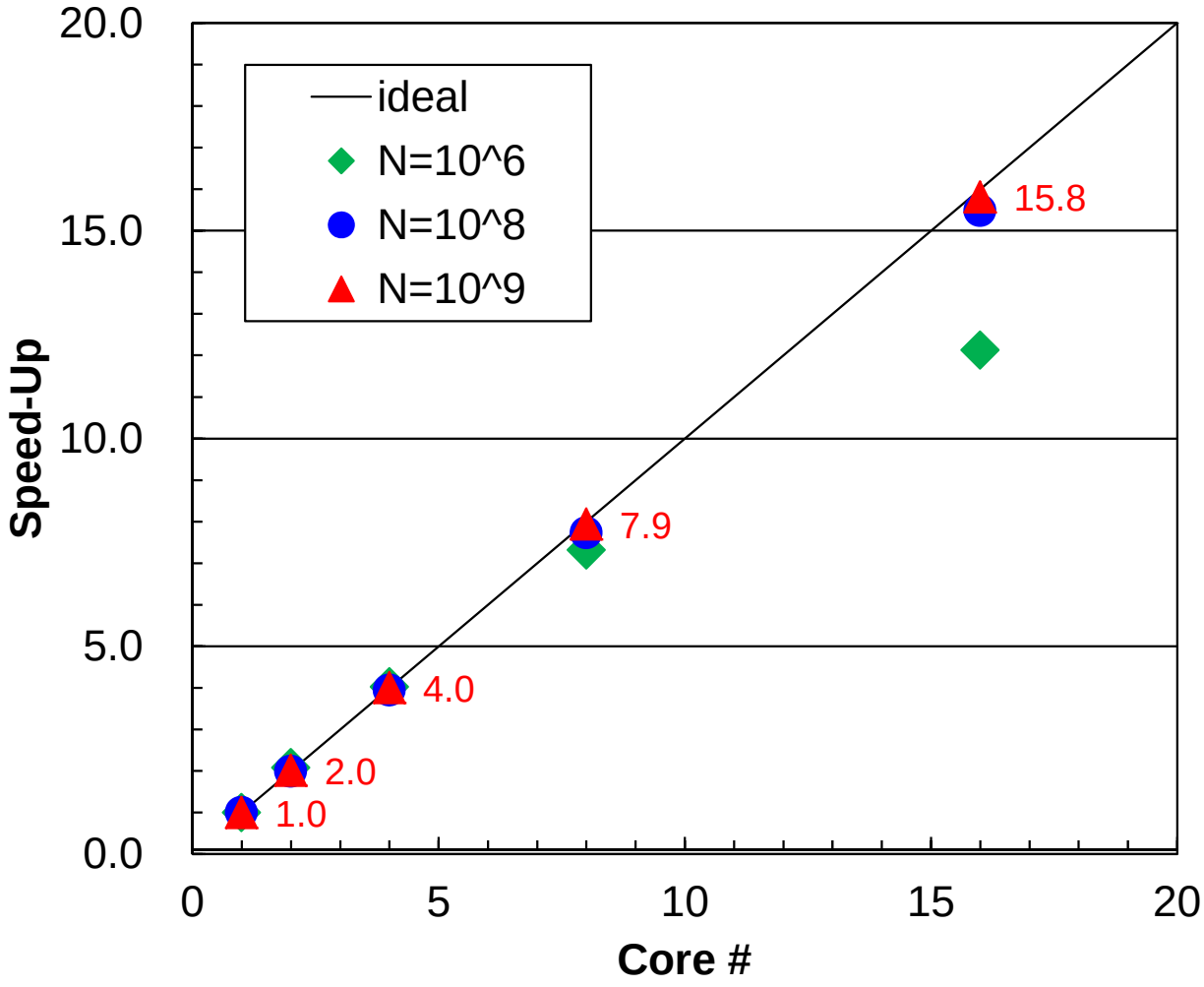
- x 7.1 at 16 cores, because of memory contention
  - STREAM
  - NOT mainly because of communication overhead



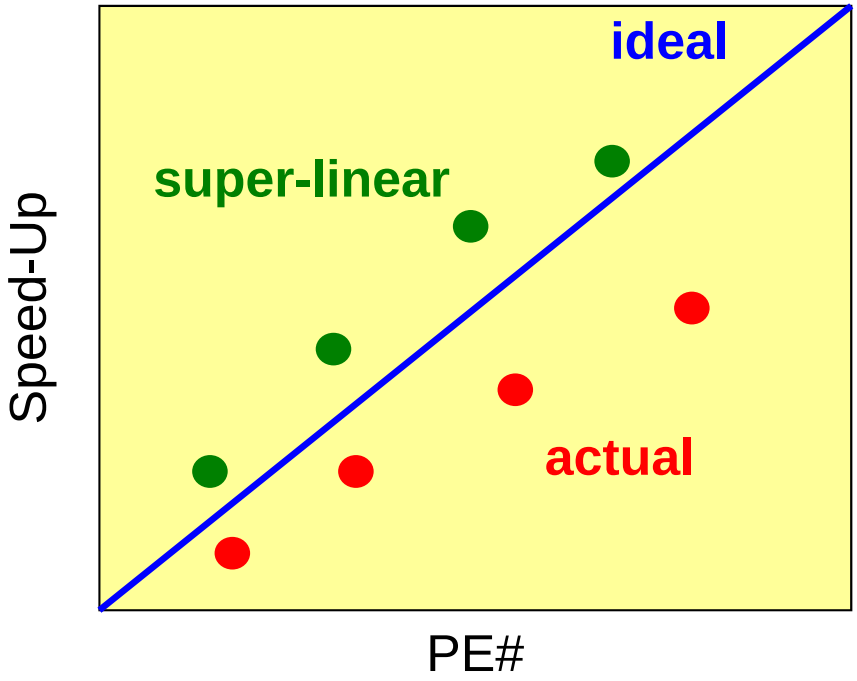
Not so significant in S1-3

- ◆ : N=10^6, ● : 10^8, ▲ : 10^9, — : Ideal
- Based on performance at a single core (sec.)

- Trapezoidal rule: requirement for memory is very small (no arrays), NON memory-bound application

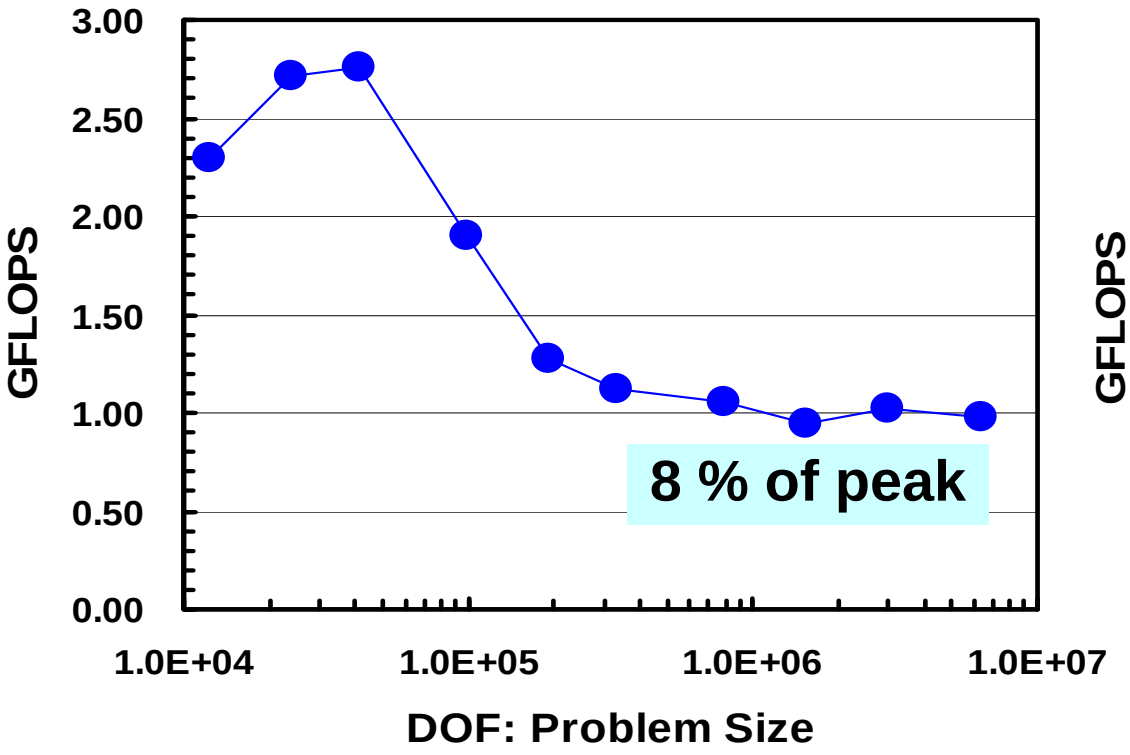


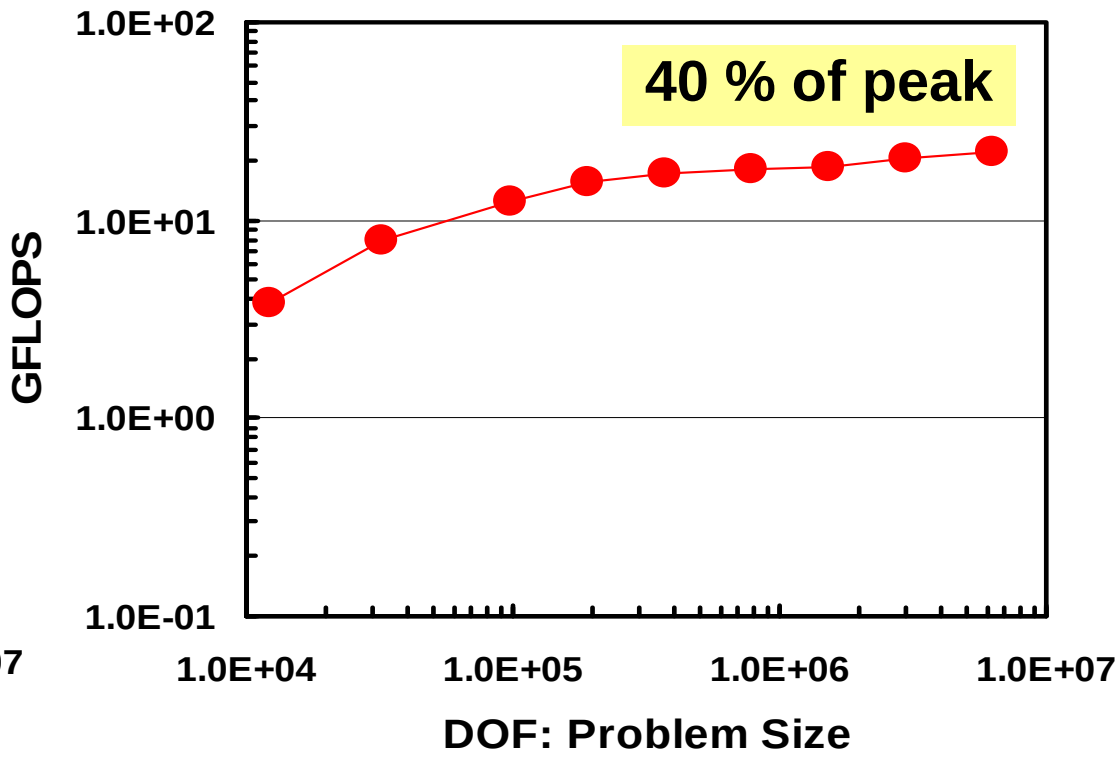
Super-Linear in Strong Scaling



- In strong scaling case where entire problem size is fixed, performance is generally lower than the ideal one due to communication overhead.
- But sometime, actual performance may be better than the ideal one. This is called “super-linear”
  - only for scalar processors
  - does not happen in vector processors

Typical Behaviors

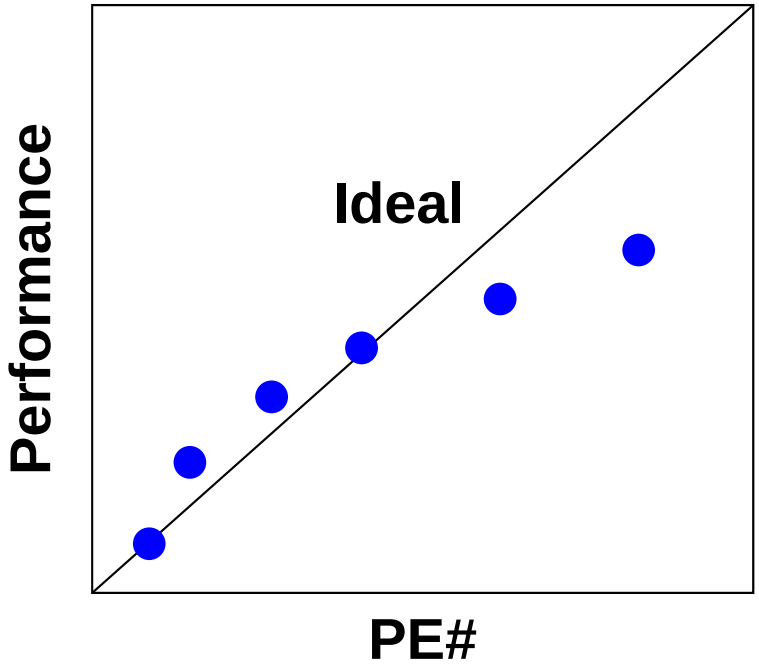


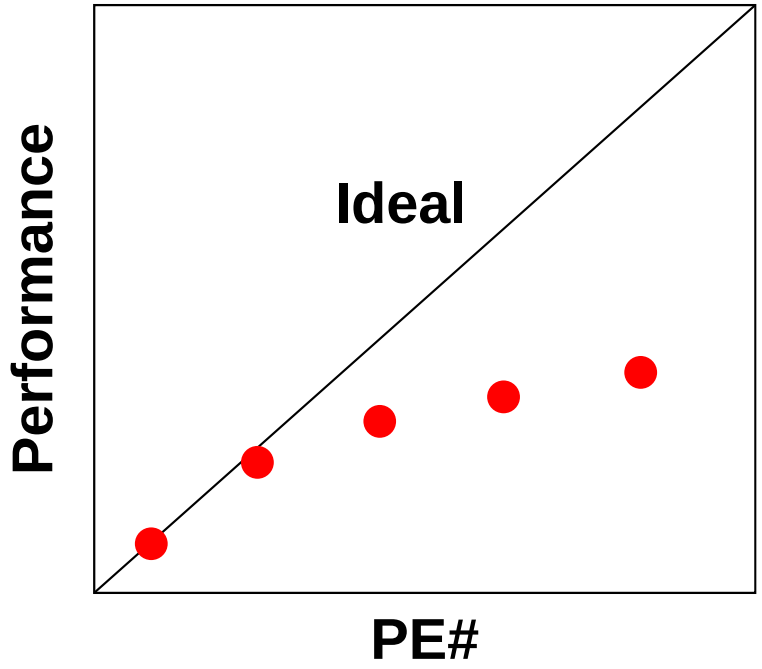


IBM-SP3:
Higher performance for small problems, effect of cache

Earth Simulator:
Higher performance for large-scale problems with longer loops

Strong Scaling



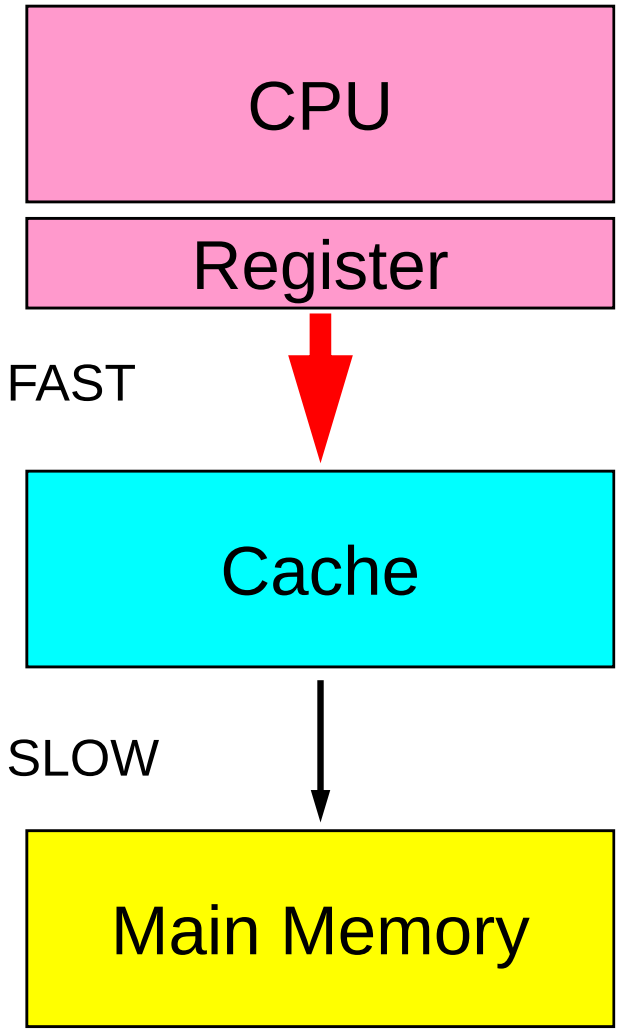


IBM-SP3:
"Super-linear" happens if number of PE is not so large. Performance is getting worse due to communication overhead if PE number is larger.

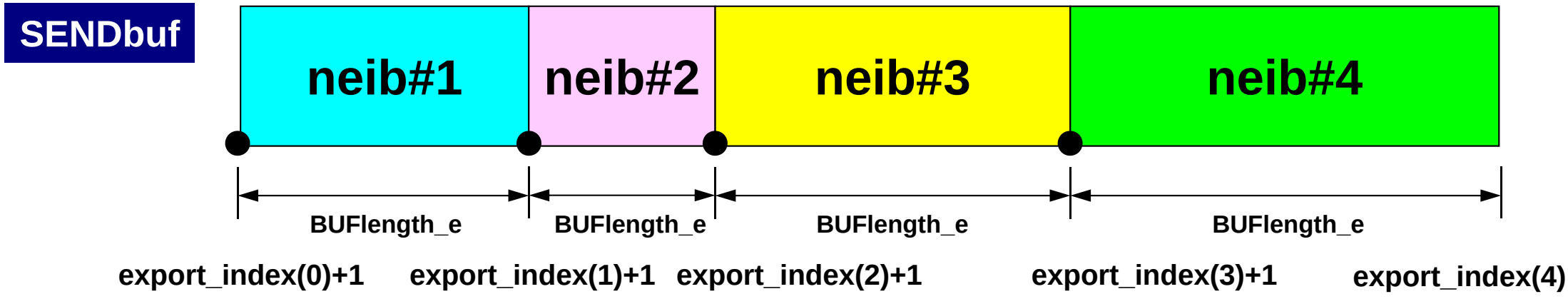
Earth Simulator:
Performance is getting worse due to communication overhead and smaller loop length if PE number is larger.

Why does “Super-Linear” happen ?

- Effect of Cache
- In scalar processors, performance for smaller problem is generally better.
  - Cache is well-utilized.



Memory Copy is expensive (1/2)



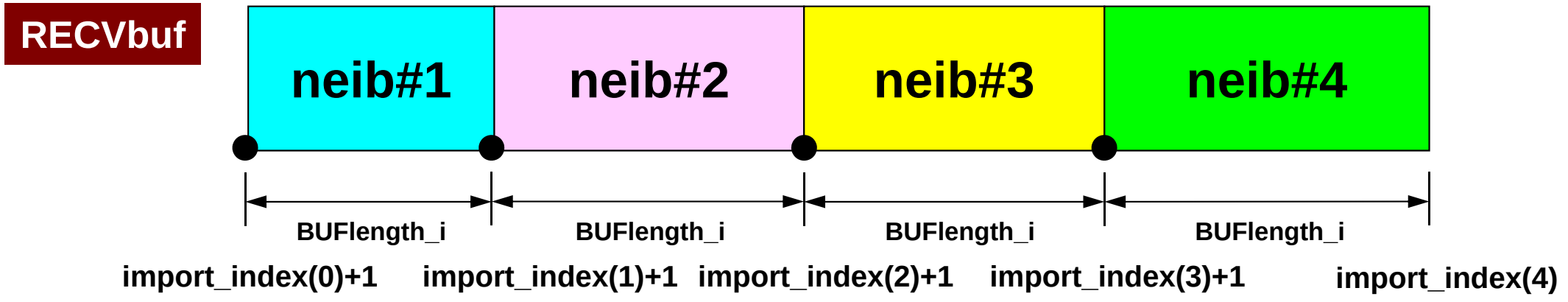

```
 do neib= 1, NEIBPETOT
   do k= export_index(neib-1)+1, export_index(neib)
     kk= export_item(k)
     SENDbuf(k)= VAL(kk)
   enddo
 enddo

 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

 call MPI_WAITALL (NEIBPETOT, request_send, stat_recv, ierr)
```

Copied to sending buffers

Memory Copy is expensive (2/2)

```
  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

  call MPI_WAITALL (NEIBPETOT, request_recv, stat_recv, ierr)

  do neib= 1, NEIBPETOT
     do k= import_index(neib-1)+1, import_index(neib)
       kk= import_item(k)
       VAL(kk)= RECVbuf(k)
     enddo
  enddo
```

Copied from receiving buffer



Summary: Parallel FEM

- Proper design of data structure of distributed local meshes.

- Open Technical Issues
  - Parallel Mesh Generation, Parallel Visualization
  - Parallel Preconditioner for Ill-Conditioned Problems
  - Large-Scale I/O

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