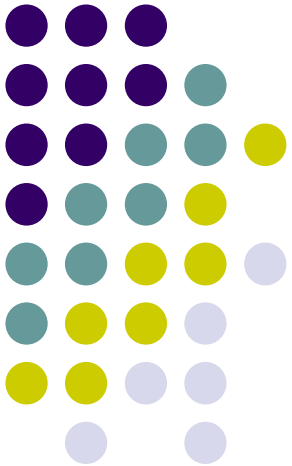
Practical Parallel Computing (実践的並列コンピューティング)



Part 3: MPI

No 3: Communication Costs

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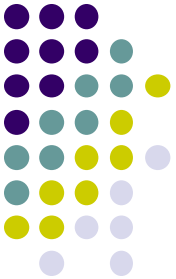
Overview of This Course



- Part 0: Introduction
  - 2 classes
- Part 1: OpenMP for shared memory programming
  - 4 classes
- Part 2: GPU programming
  - 4 classes ← We are here (1/4)
  - OpenACC (1.5 classes) and CUDA (2.5 classes)
- Part 3: MPI for distributed memory programming
  - 4 classes ← We are here (3/4)

“mm” sample: Matrix Multiply

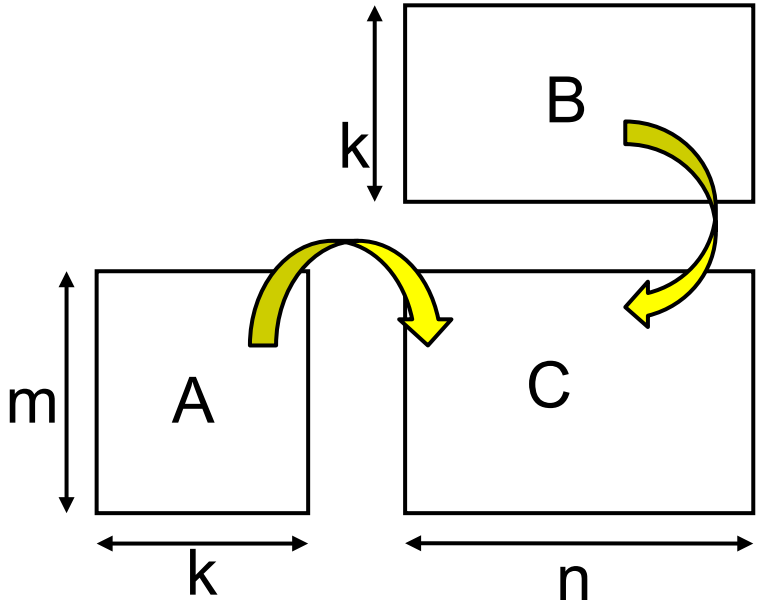
MPI version available at /gs/bs/tga-ppcomp/24/mm-mpi/

A: a (m × k) matrix, B: a (k × n) matrix

C: a (m × n) matrix

C ← A × B

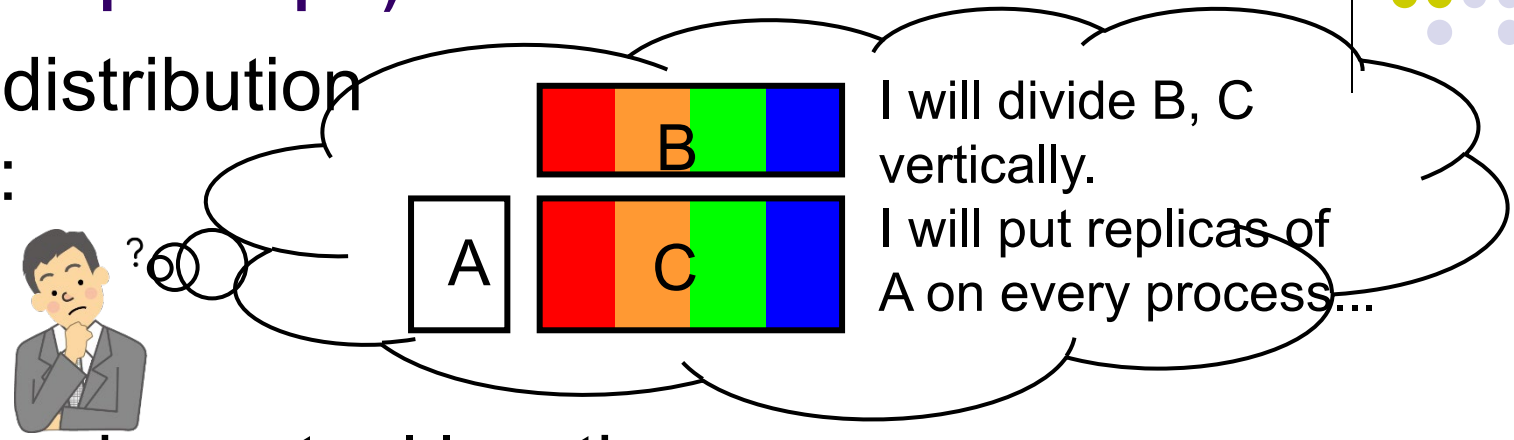
- Algorithm with a triple for loop
- Supports variable matrix size.
  - Each matrix is expressed as a 1D array by *column-major* format



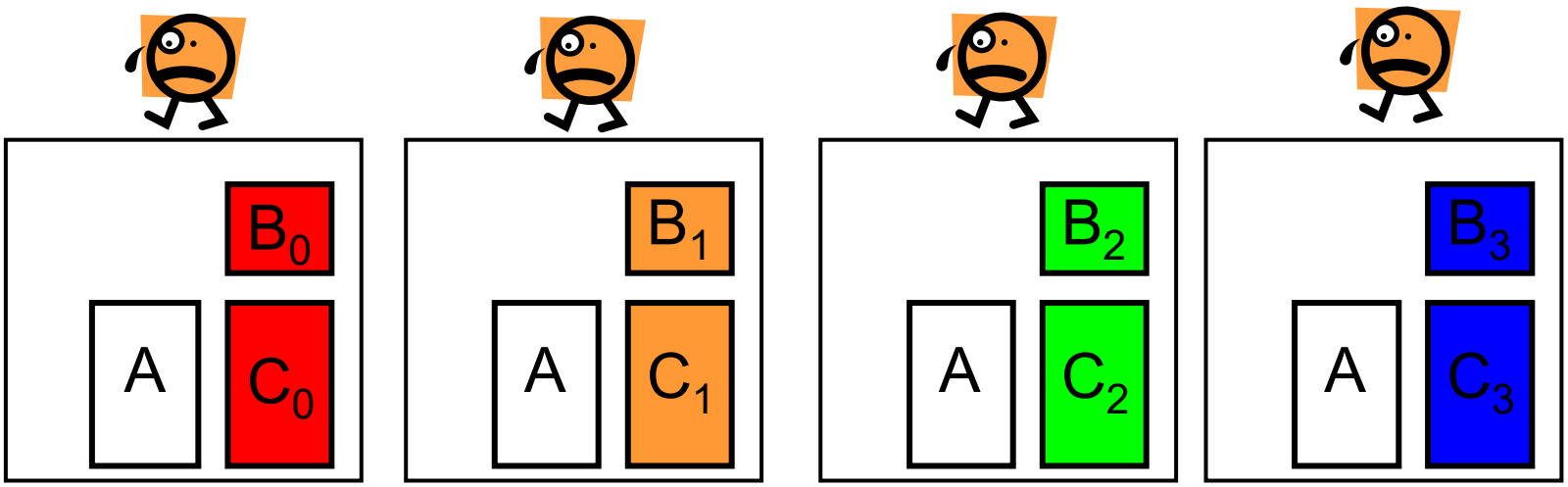
Execution: mpiexec -n [#proc] ./mm [m] [n] [k]

Programming Data Distribution
(for mm-mpi sample)

Design distribution method:



Programming actual location:



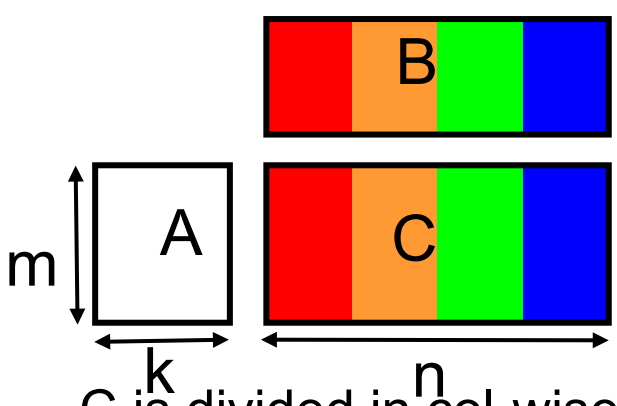
This is not a unique way. Let us discuss other ways

Discussion on Considering Data Distribution

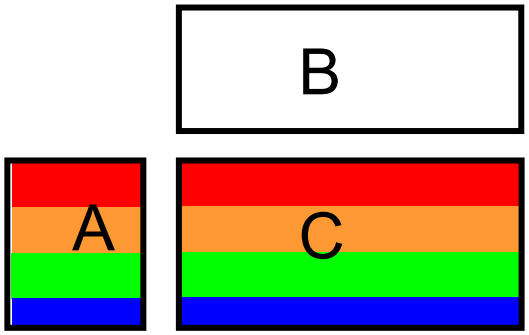
- Choice of data distribution have impact on
  - Communication cost
  - Memory consumption cost
    - In mm-mpi, every process has a copy of matrix A → memory consumption is larger ☹
- Smaller cost is better

Other Data Distribution Methods?

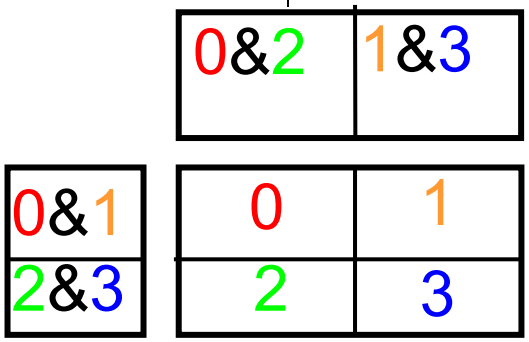
- $C_{i,j}$ requires *i*-th row of A and *j*-th column of B



C is divided in col-wise
⇒ Similarly B
A is replicated



C is divided in row-wise
⇒ Similarly A
B is replicated



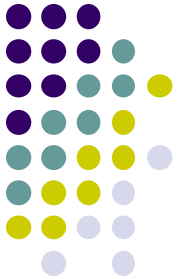
C is divided in 2D
⇒ A:row-wise + replica
B:col-wise + replica

Total Comm.	0	0	0
Totel Mem.	O(mkp+nk+mn)	O(mk+nkp+mn)	O(mkp$^{1/2}$+nkp$^{1/2}$+mn)

p: the number of processes
Note: If initial matrix is owned by one process, we need communication before computation

Among them, the third version has lowest memory consumption

Reducing Memory Consumption Further



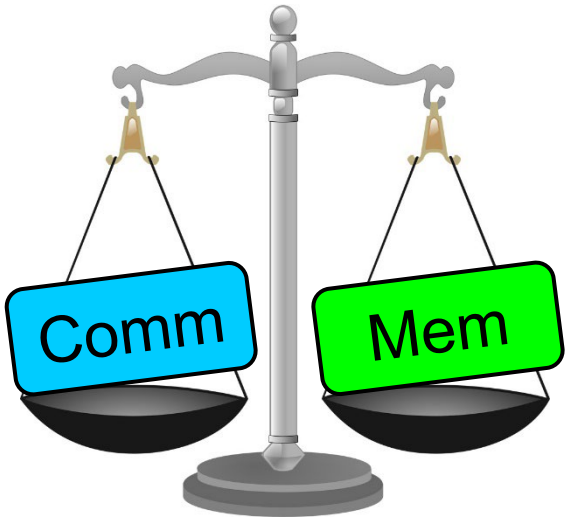
- Even in the third version, memory consumption is $O(mkp^{1/2}+nkp^{1/2}+mn)$ > $O(mk+nk+mn)$ (theoretical minimum)
- If p=10000, we consume 100x larger memory ☹

→ we cannot solve larger problems on supercomputers

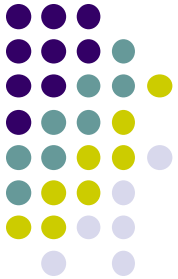
- To reduce memory consumption, we want to eliminate replica!

→ But this increases communication costs

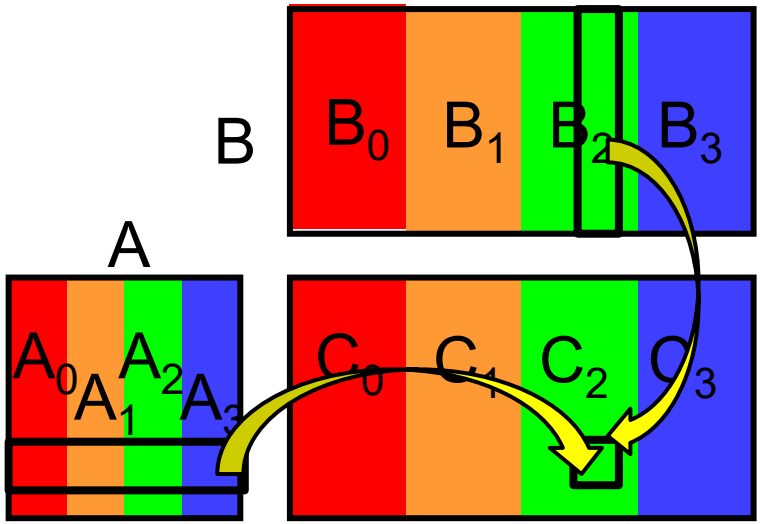
Trade-off: a balance achieved between two desirable but incompatible features



Data Distribution of Memory Reduced "mm" (related to [M2])



- Not only B and C, but A is divided among all processes (In this example, column-wise)

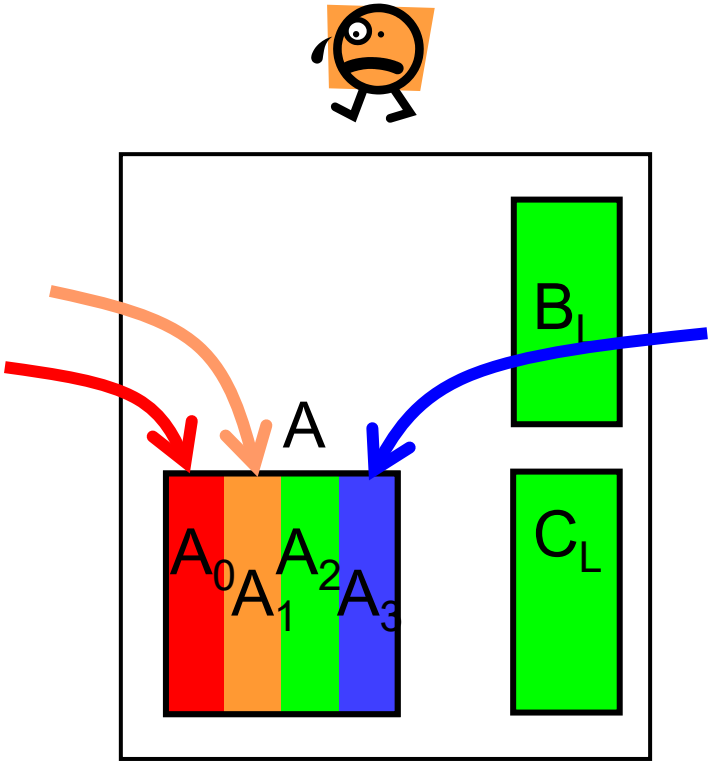


Memory consumption is smallest

- But computing each C element requires data on other processes ➔ We need communication !

How We Proceed Computation with Others' Data

- The following algorithm is not good for memory consumption

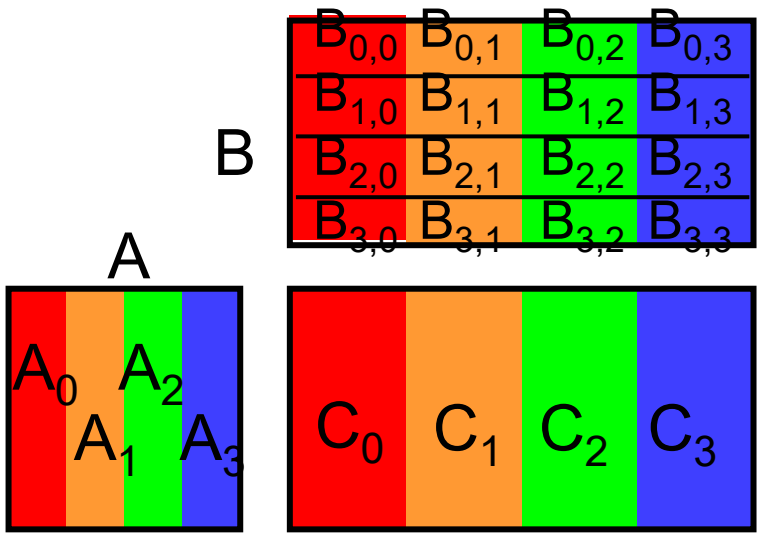


1. Collect entire A from other processes by communication
2. Compute $C_L = A \times B_L$

- Each process has (entire) A, B_L, C_L ➔ Same as mm-mpi ☹

We should avoid computation of $C_L = A \times B_L$ at once

Algorithm of Memory Reduced "mm"



If we have A only partially, we can only do $C_L = A \times B_L$ partially

Algorithm

Step 0 :

P_0 sends A_0 to all other processes

Every process P_r computes

$C_r \mathrel{+}= A_0 \times B_{0,r}$

Step 1 :

P_1 sends A_1 to all other processes

Every process P_r computes

$C_r \mathrel{+}= A_1 \times B_{1,r}$

:

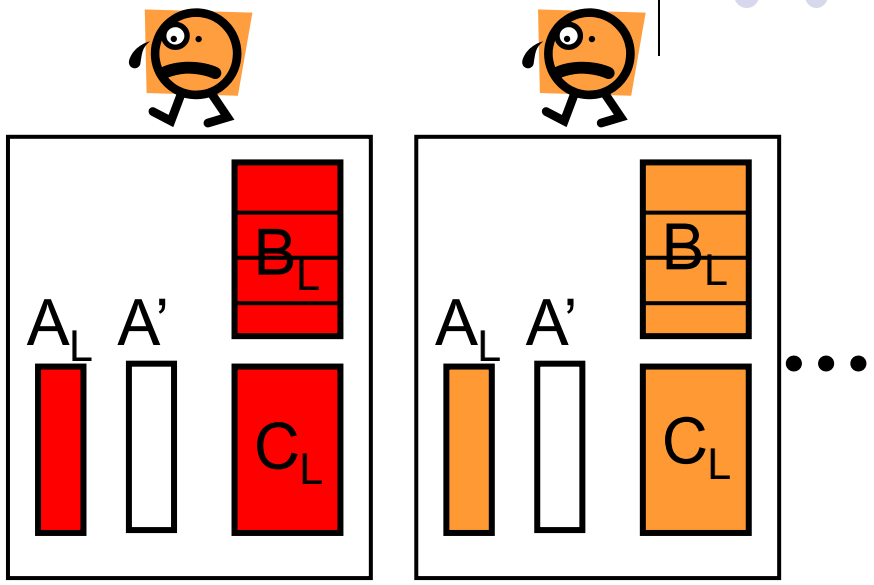
Repeat until *Step (p-1)*

Total Comm: O(mkp) Total Mem: O(mk+nk+mn)

Actual Data Distribution

Every process has partial A, B, C

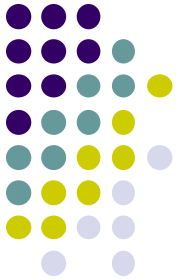
- A_L on process r ⇔ A_r
- B_L on process r ⇔ B_r
- C_L on process r ⇔ C_r



- Additionally, every process should prepare a receive buffer ➔ A' in the figure
  - A' (instead of A_L) is used for arguments of MPI_Recv()
  - On receivers, A' is used for computation

[Q] What if a process uses A_L for MPI_Recv()'s target ?

Programming Memory Reduced mm

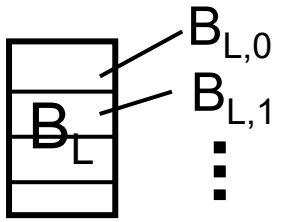


On every process r:

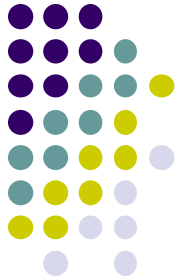
```
for (s = 0; s < p; s++) {   // s: step no, p: number of processes
    if (r == s) {
        for (dest = 0; dest < p; dest++)
            if (dest != r) MPI_Send(A_L, …, dest, …);
    } else
        MPI_Recv(A', …, s, …);

    if (r == s)
        Compute C_L += A_L × B_L,s
    else
        Compute C_L += A' × B_L,s
}
```

P_s sends its A_L to all other processes

Receives data (P_s's A_L) and stores it to A'

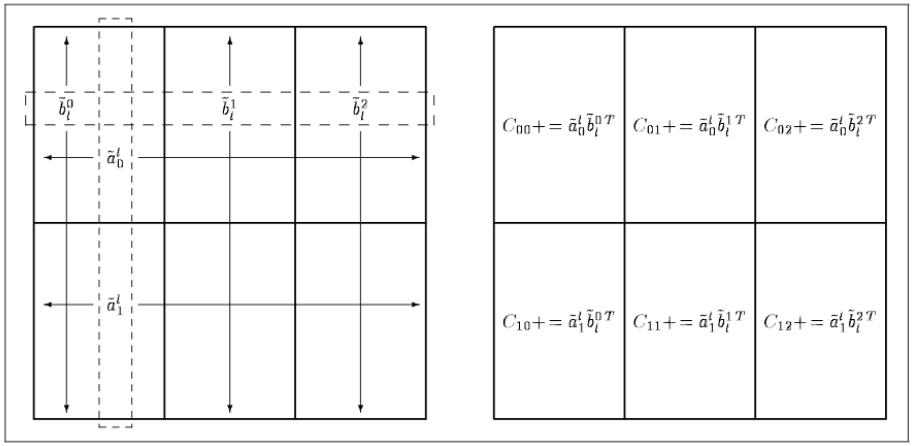


[Options] Improvements of Memory Reduced Version



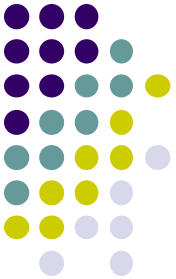
Followings are options (NOT mandatory) in assignments [M2]

1. To use SUMMA: scalable universal matrix multiplication algorithm
   - See http://www.netlib.org/lapack/lawnspdf/lawn96.pdf
   - Replica is eliminated, and matrices are divided in 2D

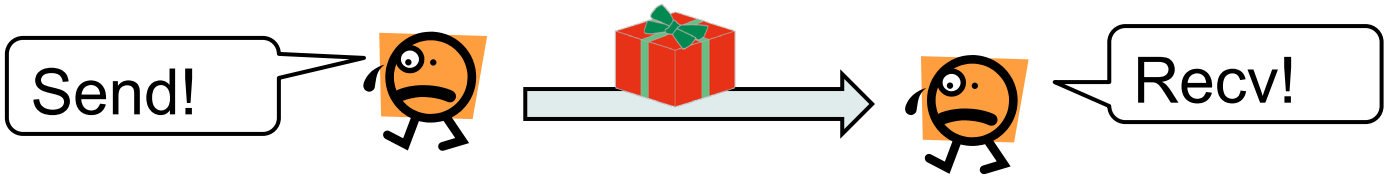


2. To use collective communications (explained hereafter)

Peer-to-peer Communications vs Collective Communications



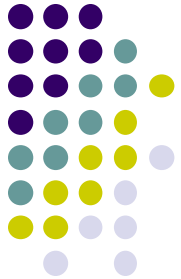
- Communications we have learned are called peer-to-peer communications
- A process sends a message. A process receives it



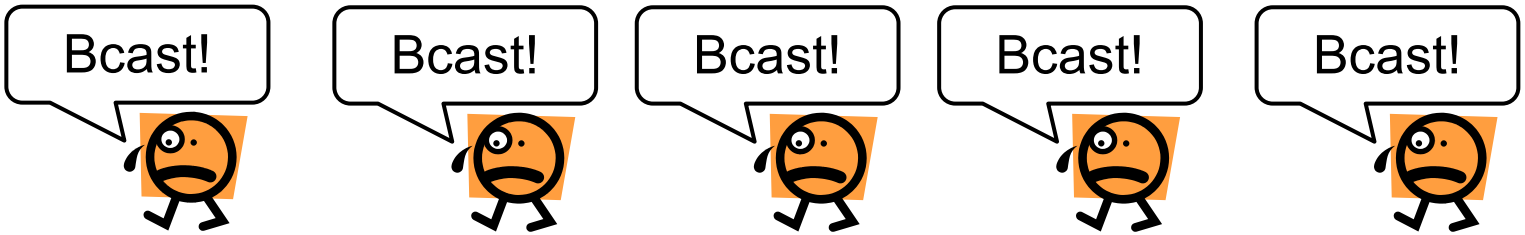
※ MPI_Irecv, MPI_Isend are also peer-to-peer communications

	Blocking	Non-Blocking
Peer-to-Peer	MPI_Send, MPI_Recv…	MPI_Isend, MPI_Irecv…
Collective	MPI_Bcast, MPI_Reduce…	(MPI_Ibcast, MPI_Ireduce…)

Collective Communications (Group Communications)

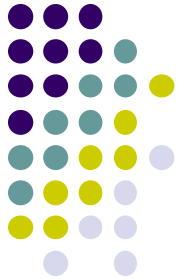


- Collective communications involves many processes
  - MPI provides several collective communication patterns
    - Bcast, Reduce, Gather, Scatter, Barrier・・・
  - All processes must call the same communication function



→ Something happens for all of them

One of Collective Communications: Broadcast by MPI_Bcast

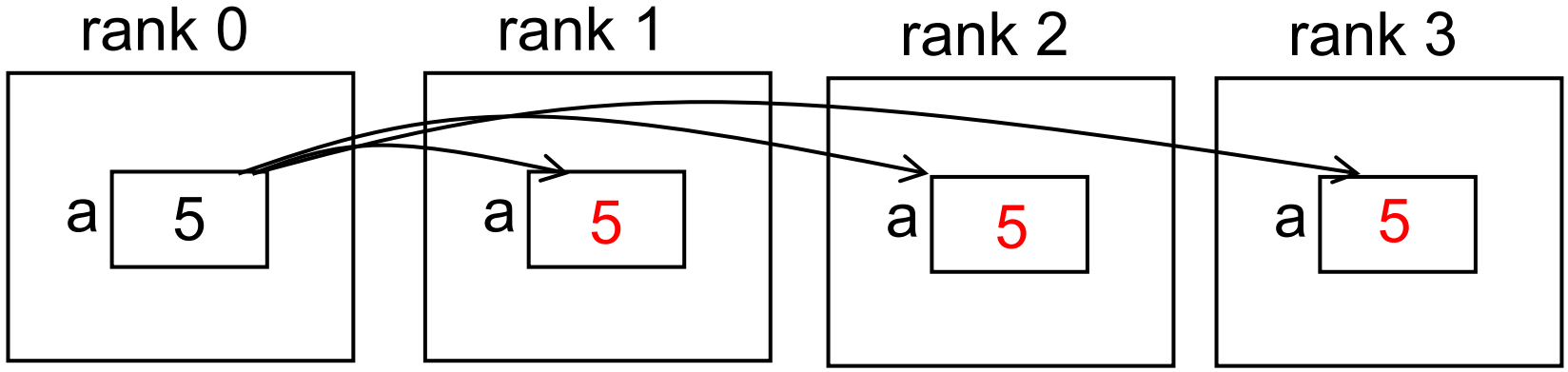


cf) rank 0 has “int a” (called root process). We want to send it to all other processes

```
MPI_Bcast(&a, 1, MPI_INT, 0, MPI_COMM_WORLD);
```

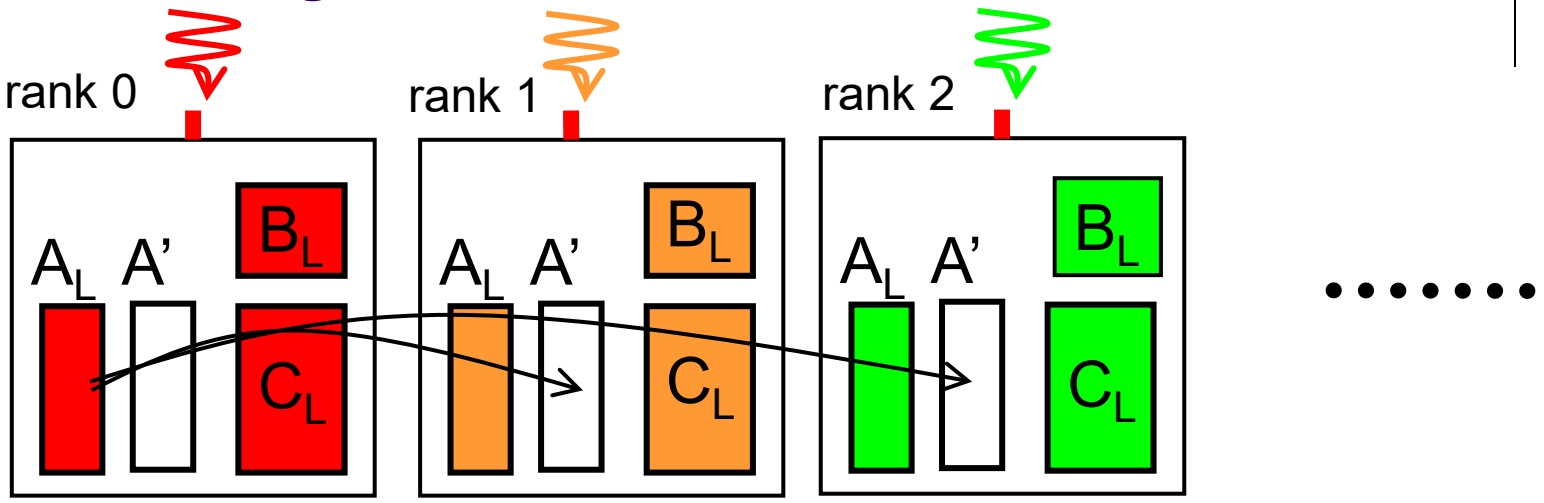
- All processes (in the communicator) must call MPI_Bcast(), including rank 0

→ All other process will receive the value on memory region a



※ What is the role of 1st argument?
it is “input” on the root process, and “output” on other processes

MPI_Bcast Can Be Used in Memory Reduced MM [M2]



- In Step i, rank i becomes the root
- It sends A_L to all other processes

→ This is "broadcast" pattern. We can use MPI_Bcast!

Note: Root wants to send A_L. Others want to receive data into A'
→ Different pointers

Solution 1:
if (I am rank i) copies A_L to A'
MPI_Bcast(A', …);

Solution 2:
if (I am rank i) {MPI_Bcast(A_L, …); }
else {MPI_Bcast(A', …); }

Reduction by MPI_Reduce

cf) Every process has “int a”. We want the sum of them

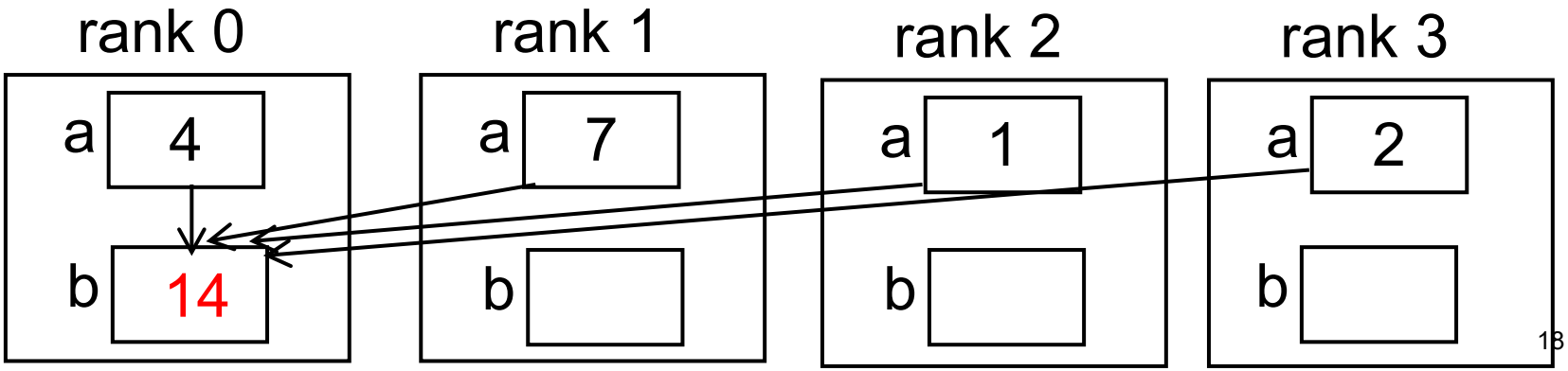
```
MPI_Reduce(&a, &b, 1, MPI_INT, MPI_SUM, 0,
           MPI_COMM_WORLD);
```

operation *root process*

- Every process must call MPI_Reduce()

→ The sum is put on b on root process (rank 0 now)

- Operation is one of MPI_SUM, MPI_PROD(product), MPI_MAX, MPI_MIN, MPI_LAND (logical and), etc.



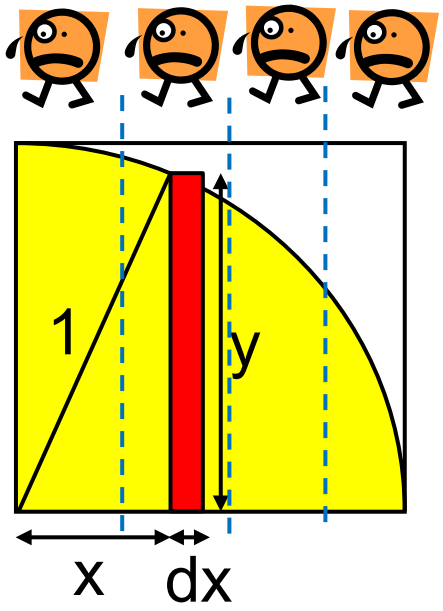
MPI Version of “pi” Sample

/gs/bs/tga-ppcomp/24/pi-mpi/

- Execution : mpiexec -n [#procs] ./pi [n]
  - n: Number of division
  - Cf) ./pi 100000000

- We divide *n* tasks among processes and calculate total yellow area

1. Each process calculates local sum
2. Rank 0 obtains the final sum by MPI_Reduce



dx = 1/n
y = sqrt(1-x*x)

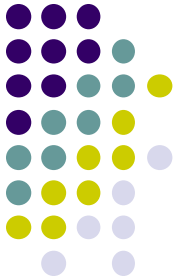
Using pi-mpi sample

- /gs/bs/tga-ppcomp/24/pi-mpi

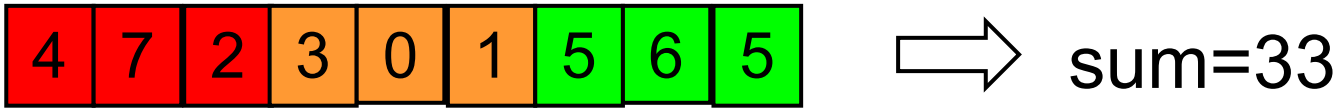
```
[make sure that you are at a interactive node (r7i7nX) ]
module load intel-mpi    [Do once after login]
cd ~/ppc24                              [In web-only route]
cp -r /gs/bs/tga-ppcomp/24/pi-mpi  .
cd pi-mpi
make
[An executable file “pi” is created]
mpiexec -n 4 ./pi 100000000
```

Number of division

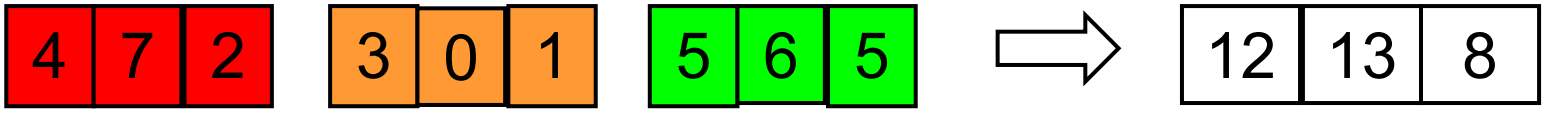
Note: Differences with "omp for reduction" in OpenMP



- Syntaxes are completely different
- Computations are also different
  - #pragma omp for reduction(…) in OpenMP
    - Do "sum += a[i]" in parallel for loop with reduction(+:sum)



  - MPI_Reduce(…) in MPI
    - If each input is an array, output is also an array
    - Operations are done for each index

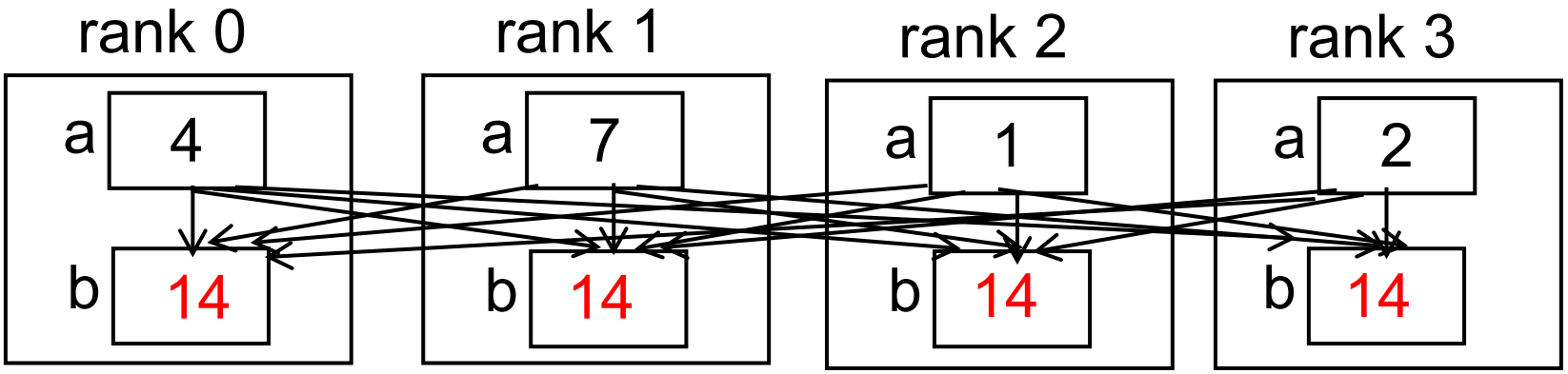


MPI_Allreduce

- Allreduce = Reduction + Bcast

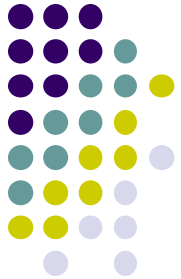
```
MPI_Allreduce(&a, &b, 1, MPI_INT, MPI_SUM,
              MPI_COMM_WORLD);
```

  - The sum is put on b on all processes



Important communication pattern for distributed deep learning → Try Google "allreduce deep learning"

MPI_Barrier

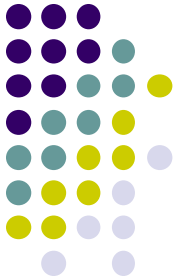


- Barrier synchronization: processes are stopped until all processes reach the point

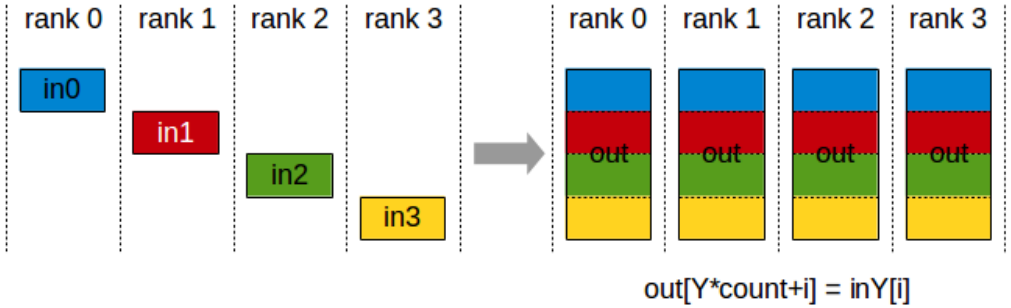
```
MPI_Barrier(MPI_COMM_WORLD);
```

  - Used in sample programs, to measure execution time more precisely

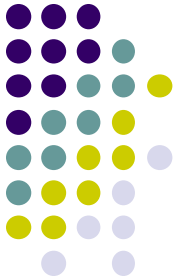
Other Collective Communications



- MPI_Scatter
  - An array on a process is “scattered” to all processes
  - cf) Process 0 has an array of length 10,000. There are 10 processes. The array is divided to parts of length 1,000 and scattered
- MPI_Gather
  - Data on all processes are “gathered” to the root process.
  - Contrary to MPI_Scatter
- MPI_Allgather
  - Similar to MPI_Gather. Gathered data are put on all processes

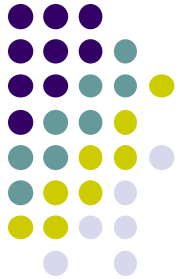


From NCCL manual at docs.nvidia.com



Performance of Collective Communication

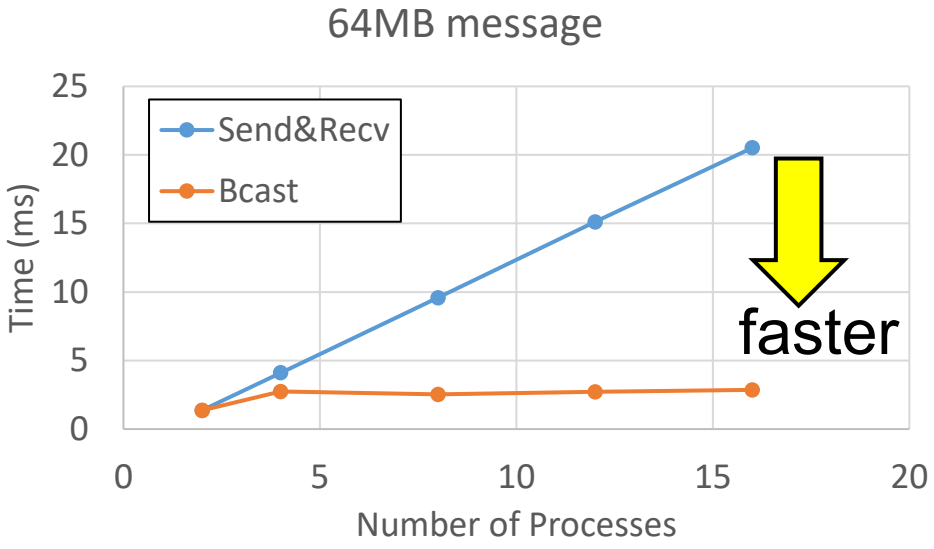
“Do I Really Need to Learn New Functions?”

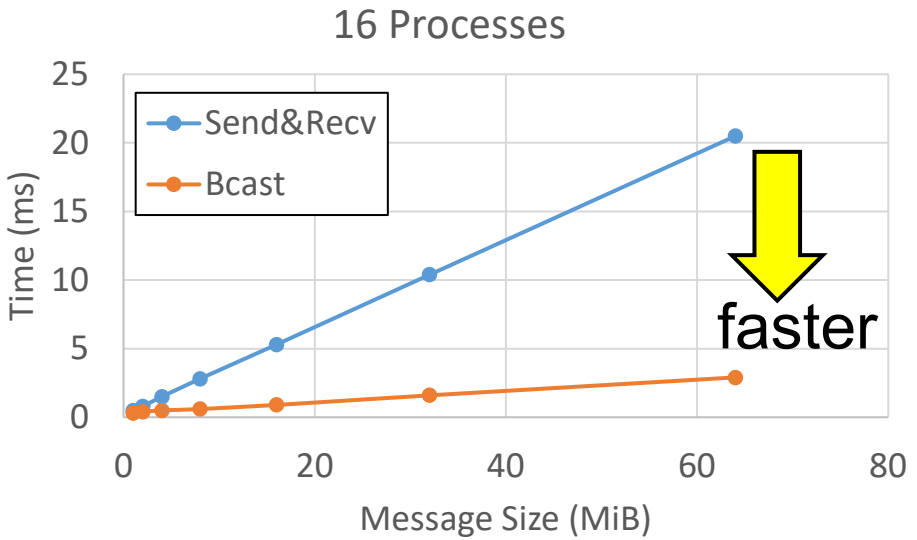


- You can still use MPI_Send/MPI_Recv multiple times, but collective functions are often faster

On TSUBAME4
1 proc / node

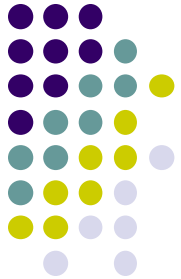
In the graph, rank 0 called MPI_Send for p-1 times to other processes





- MPI_Bcast are faster, especially when p is larger !
- The reason is MPI uses “scalable” communication algorithms:
  cf) http://www.mcs.anl.gov/~thakur/papers/mpi-coll.pdf

FYI: Measurement Method

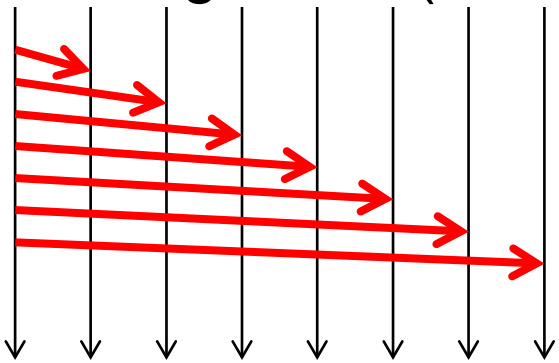


- Measurement in the previous page was done with /gs/bs/tga-ppcomp/24/mpibcast/
- intel-mpi is used
- NOTE: job*.sh in this directory need to consume TSUBAME points
  - job*.sh use > 2nodes

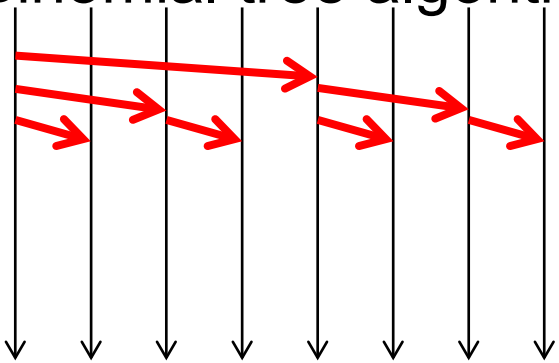
Why are Collective Communications Fast?

- Since MPI library uses *scalable* communication algorithms
  - Case of broadcast:

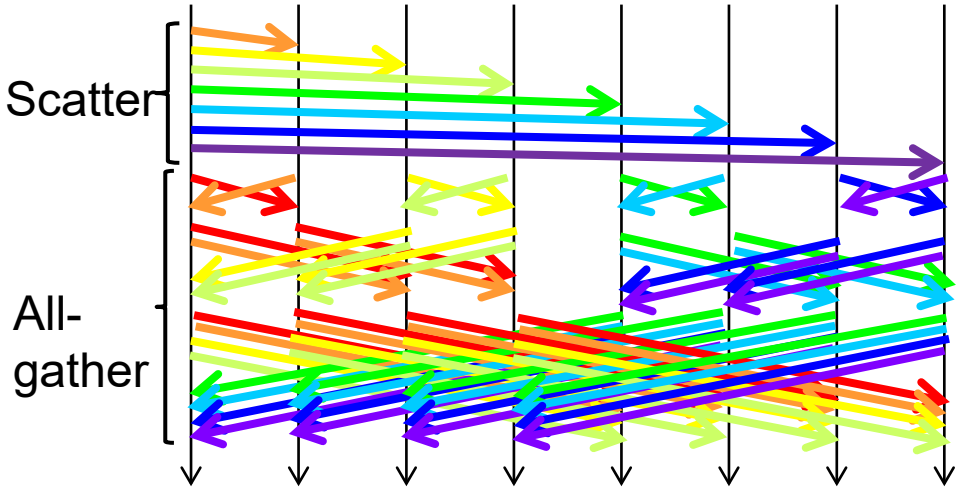
Flat tree algorithm (slow)



Binomial tree algorithm

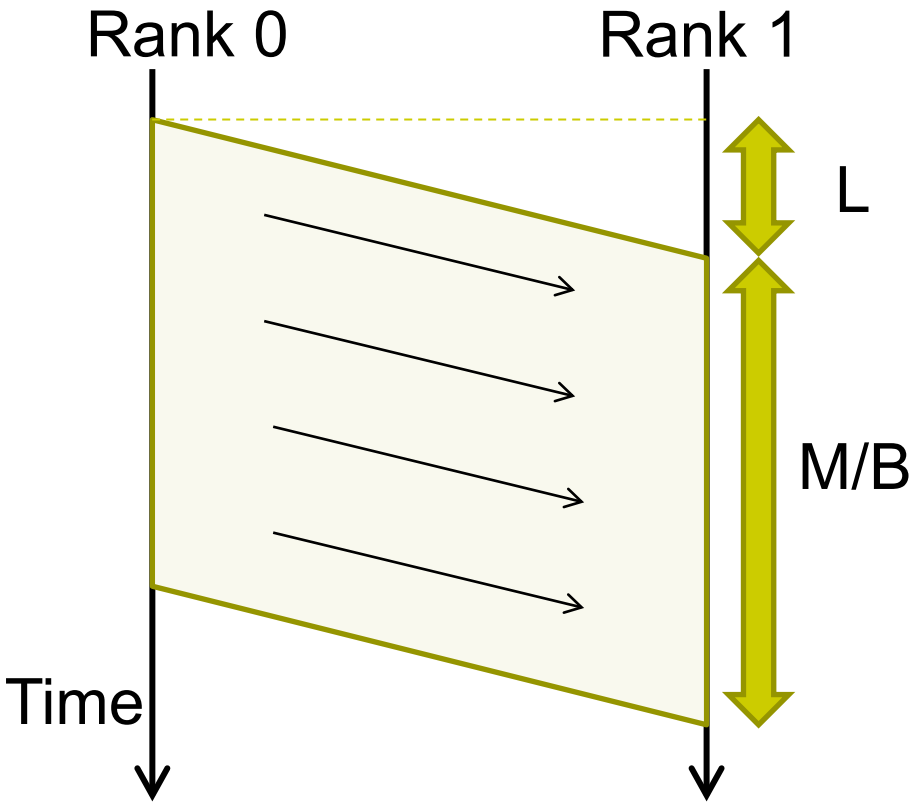


Scatter&Allgather algorithm



Model of Communication Time

Illustration of peer-to-peer communication of data size M



$$T = M / B + L$$

T: Communication time

M: Data size

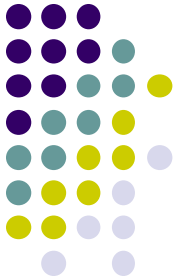
B: Bandwidth

L: Network latency

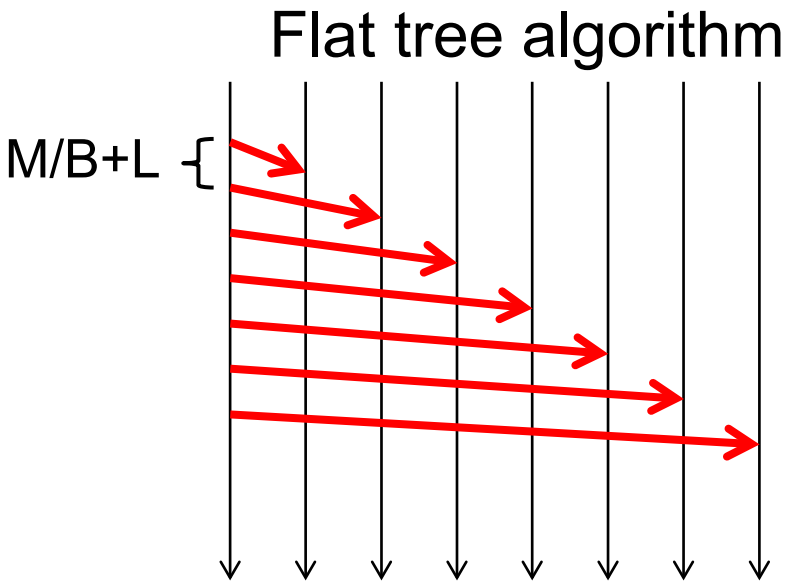
※ Be aware of difference between "Byte" and "bit": 1Byte=8bit

※ Actually it is more complex for process's place, effects of network topology, congestion, packet size…

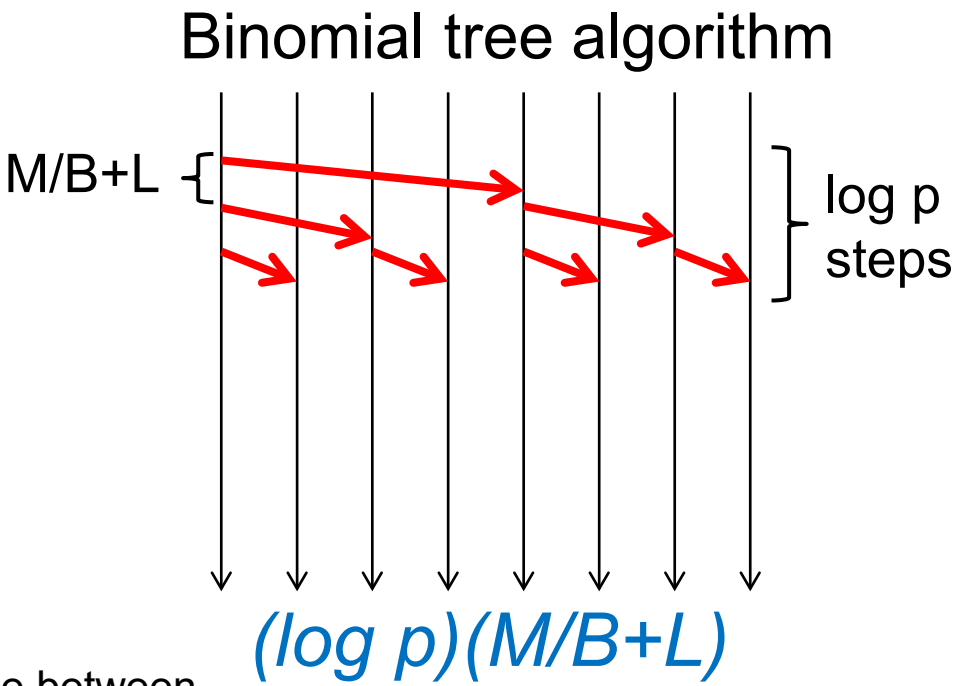
Cost Model of Broadcast Algorithms



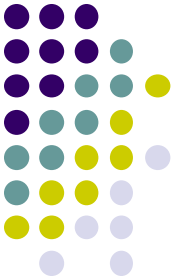
- Case of “broadcast” of size M data
  - p: number of processes, B: network bandwidth, L: network latency



※difference between p-1 and p is ignored



Broadcast by Scatter&Allgather Algorithm (1)

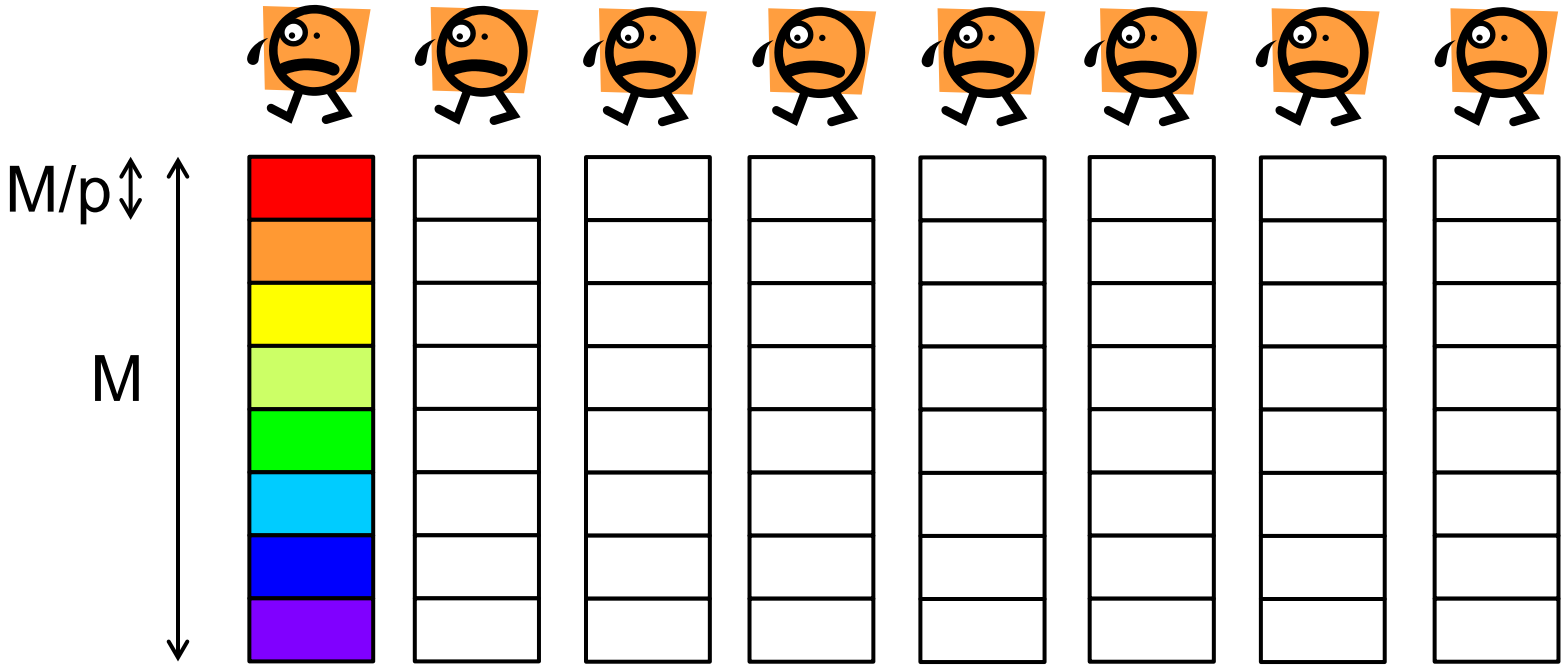


(1) The root process divide the message into p parts

(2) Scatter

(3) Allgather

R. Thakur and W. Gropp. Improving the performance of collective operations in mpich. EuroPVM/MPI conference, 2003.

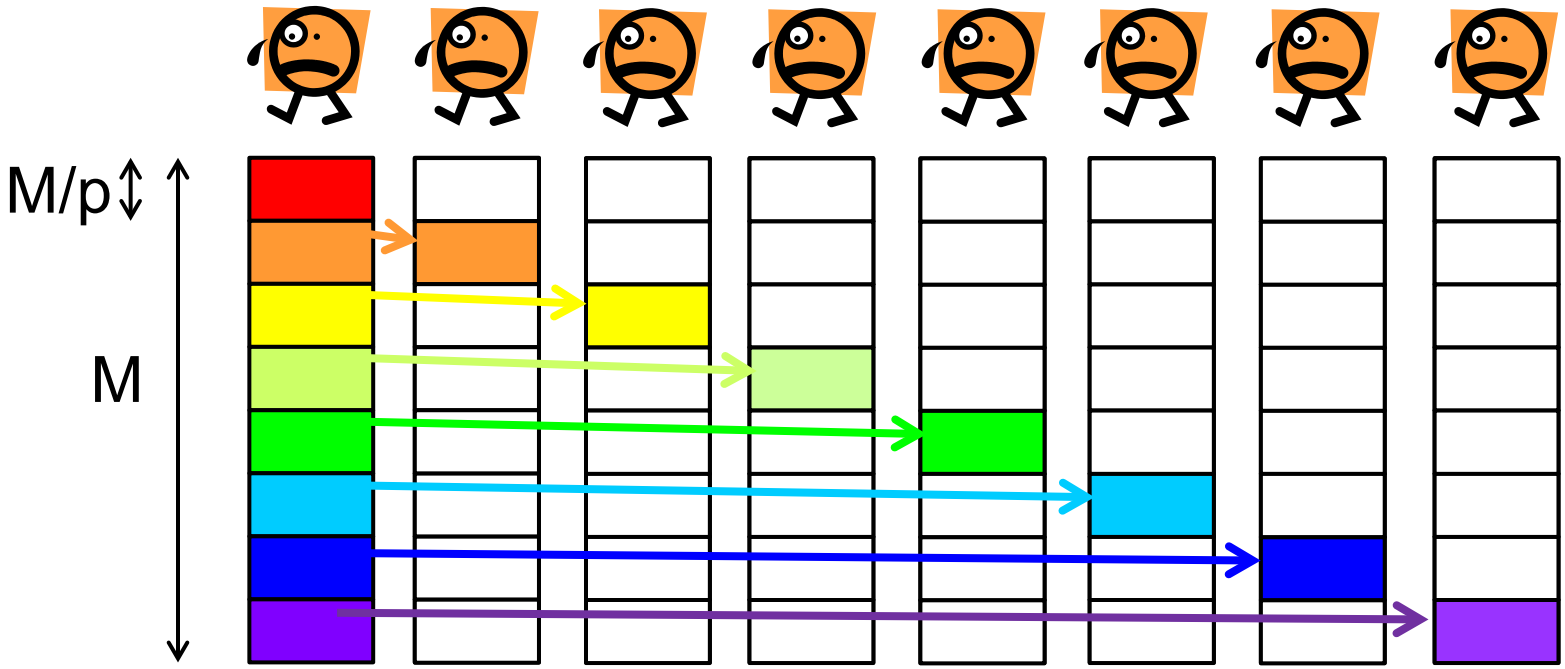


Scatter&Allgather Algorithm (2)

(1) The root process divide the message into p parts

(2) Scatter: *i*-th part goes to process *i*

(3) Allgather



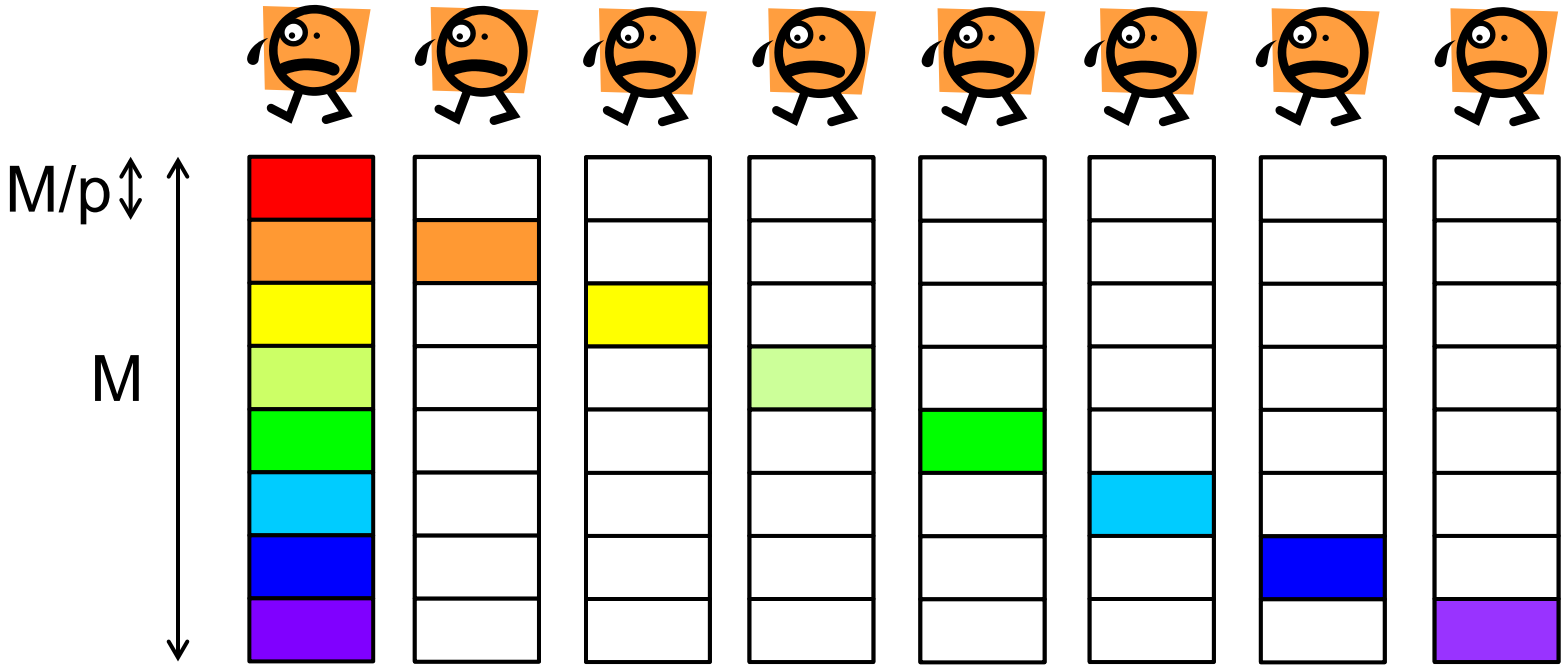
Scatter&Allgather Algorithm (3)

(1) The root process divide the message into p parts

(2) Scatter

(3) Allgather in *log p* steps

- If p=8, we use 3 steps



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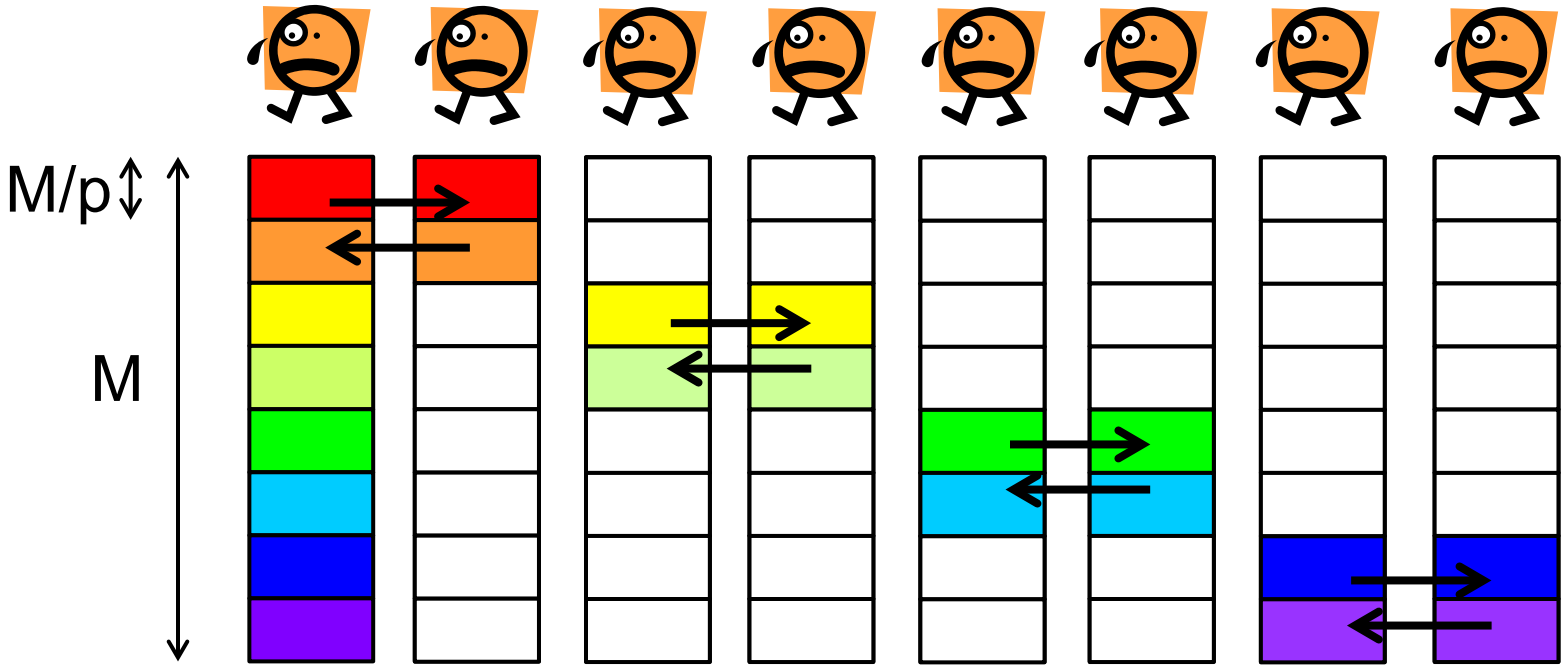

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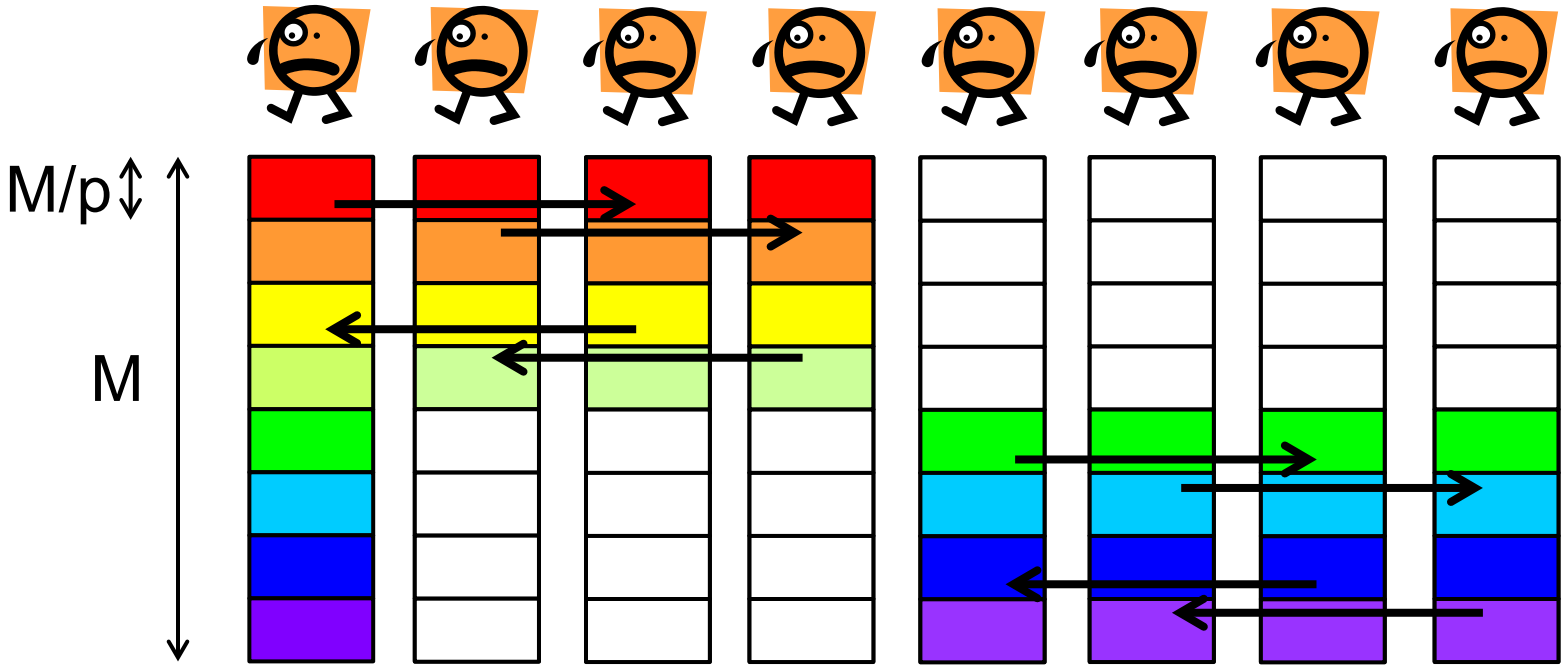

Scatter&Allgather Algorithm (3)

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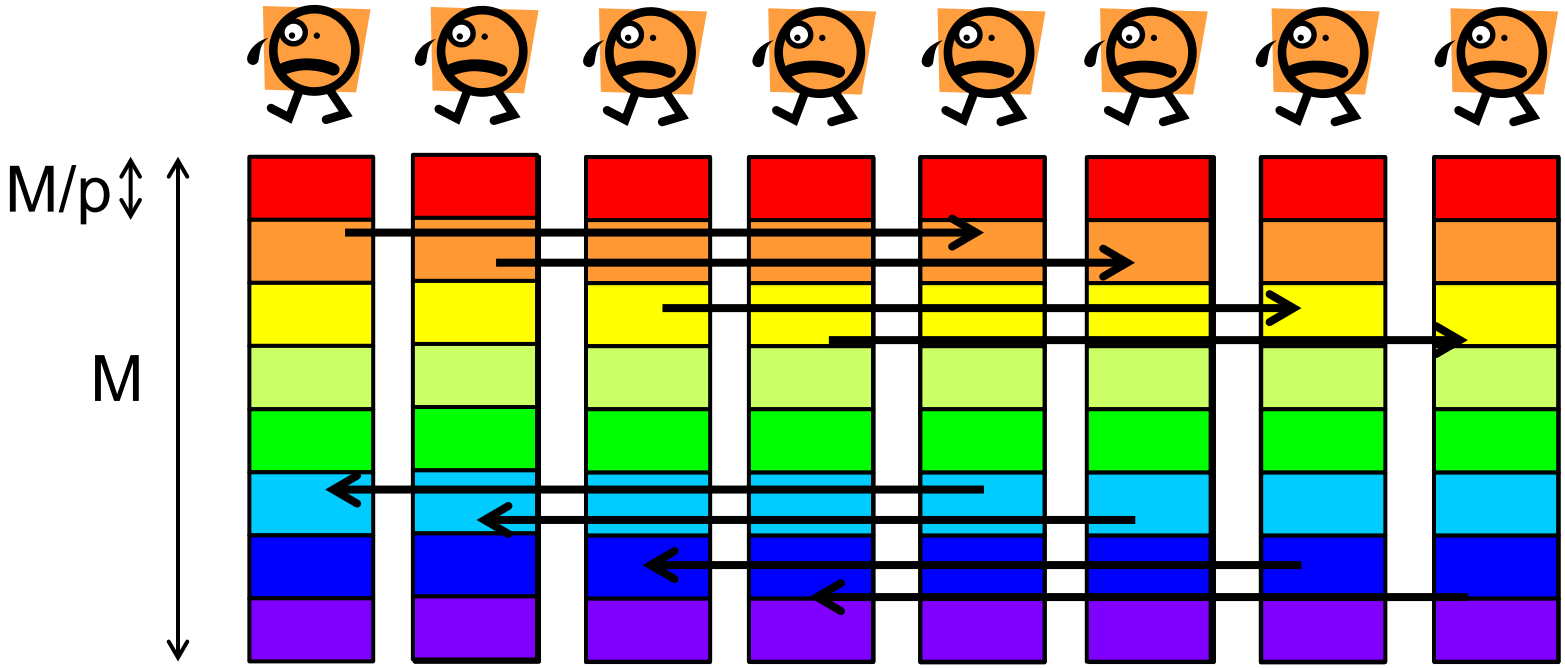
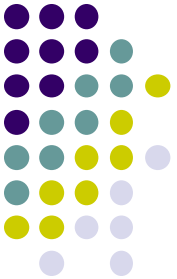
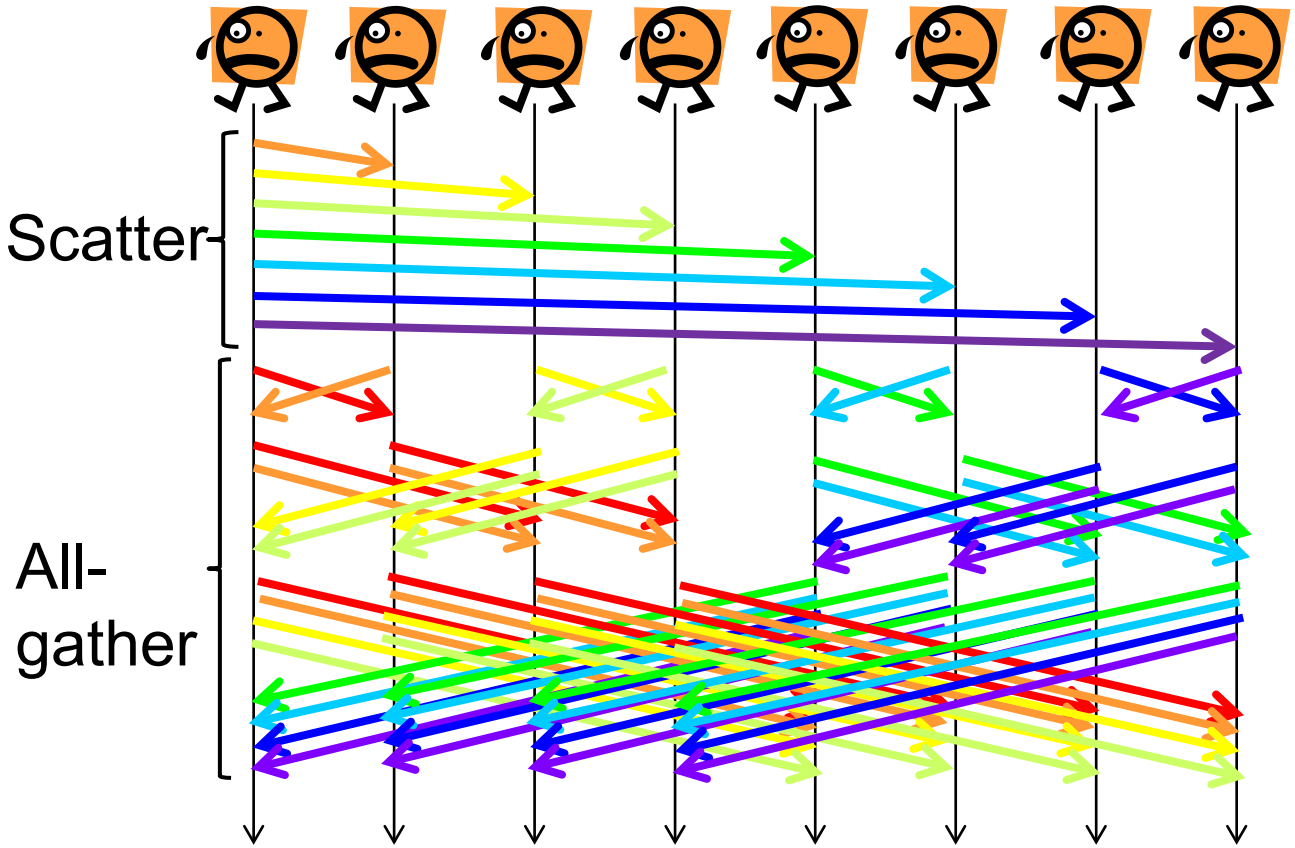


Cost of Scatter&Allgather Algorithm



- Scatter&Allgather algorithm
  (1) The root process divide the message into p parts
  (2) Scatter
  (3) Allgather



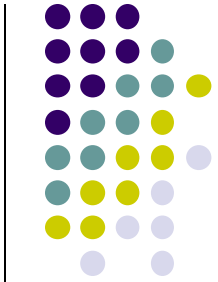
Scatter

$M/B + pL +$

$M/B + (\log p)L$

All-gather

Comparison of Broadcast Algorithms

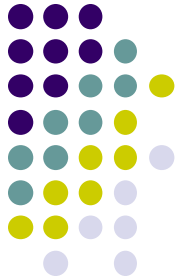


- Consider two extreme cases
  - If M is sufficiently large: *M/B+L → M/B*
  - If M is close to zero: *M/B+L → L*

	Flat Tree	Binomial Tree	Scatter& Allgather
General Cost	p(M/B+L)	(log p) (M/B+L)	2M/B + (p + log p)L
Cost with very large M (L is ignored)	p M/B	(log p) M/B	2 M/B → Fastest
Cost with very small M (M is ignored)	p L	(log p) L → Fastest	(p + log p) L

Many MPI libraries implement multiple algorithms
They switch them automatically according to message size M ☺

Assignments in MPI Part (Abstract)



Choose *one of* [M1]—[M3], and submit a report

Due date: June 13 (Thursday) (sorry, not June 14!)

[M1] Parallelize “diffusion” sample program by MPI.

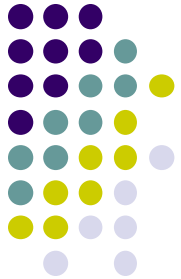
- Be careful for deadlock

[M2] Improve mm-mpi sample in order to reduce memory consumption.

[M3] (Freestyle) Parallelize *any* program by MPI.

For more detail, please see 3-1 slides

Notes in Part 3 Assignments



- It is reported that MPI programs may be sometimes very slow on TSUBAME4 CPUs
  - ½ – ¼ speeds of OpenMP programs
  - Reasons are still unclear, but considered to be related to architecture and multi-processes
- It is ok to report such slow performance

Next Class

- MPI (4)
  - Other topics about MPI and parallel computing

- Planned schedule
  - June 3: Part 3 (4): (Short) class + TSUBAME4 tour
    - If you come to the class room at 10:45, you can see TSUBAME4
    - Room 202, 2F, G2 building, Suzukake-dai campus

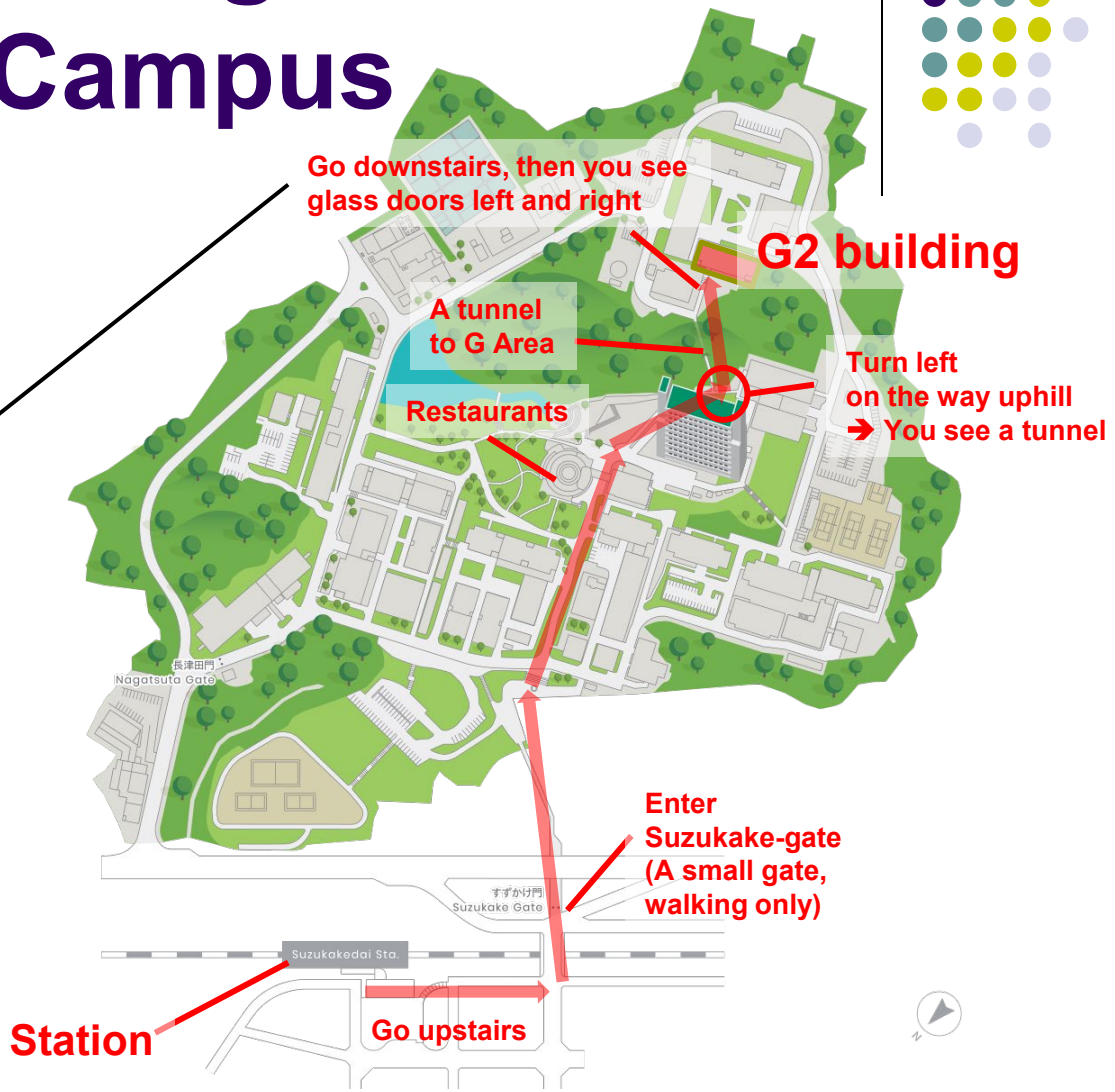
  G2 bulding: No 31 in Campus map
  https://www.titech.ac.jp/english/0/maps/suzukakedai

Way to G2 Building at Suzukakedai Campus

Suzukakedai Campus:

10 minutes walk from Suzukakedai Station, Denentoshi Line

Enter the right door and go up to the 2nd floor
→ Room 202



すずかけ台G2棟への道

すずかけ台キャンパス：

田園都市線すずかけ台駅から
約徒歩10分

202講義室：
右のドアに入り二階に上る