

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

Part 3: MPI

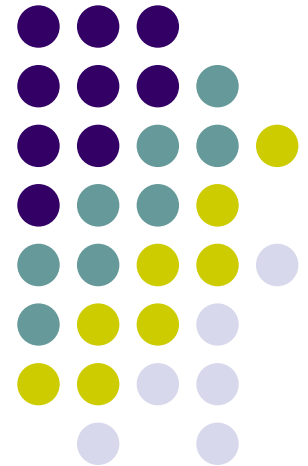
No 2: Message Passing

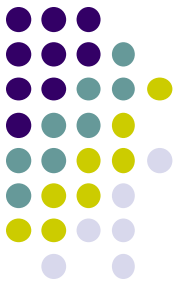
May 27, 2024

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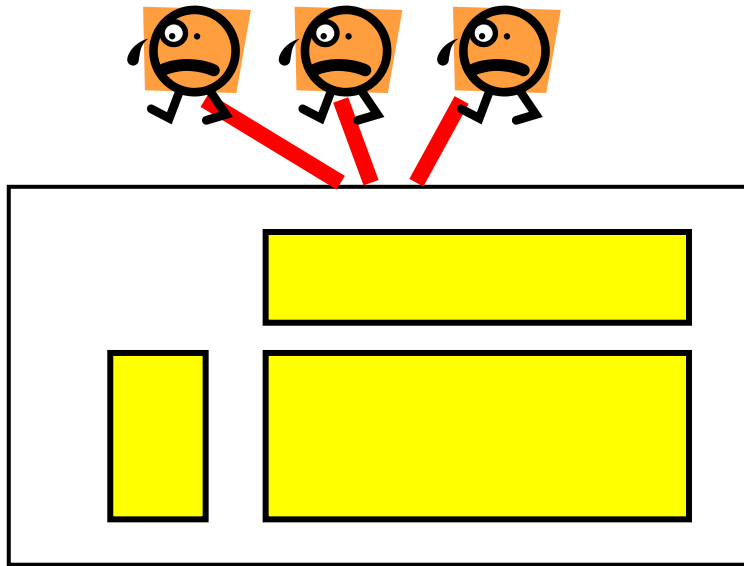
Overview of This Course

- 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 (2/4)

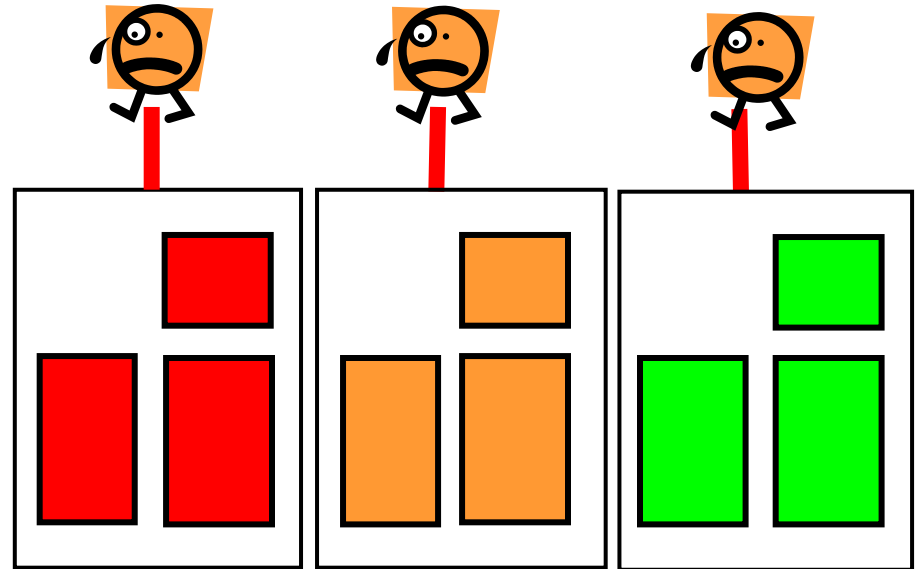
Shared Memory Model and Distributed Memory Model



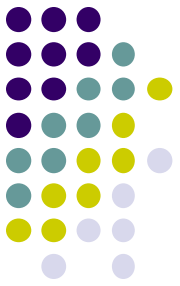
Shared Memory



Distributed Memory



- In distributed memory model, a process CANNOT read/write other processes' memory directory
- How can a process access data on others?
→ **Message passing** (communication) is required



test-mpi sample

- </gs/bs/tga-ppcomp/24/test-mpi>

[make sure that you are at a interactive node (r7i7nX)]

`module load intel-mpi` *[Do once after login]*

`cd ~/ppc24`

`cp -r /gs/bs/tga-ppcomp/24/test-mpi .`

`cd test-mpi`

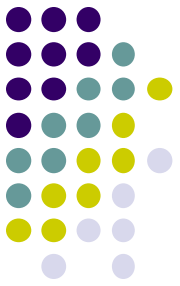
`make`

[An executable file “test” is created]

`mpiexec -n 2 ./test`

↖
This sample is for
2 processes

Basics of Message Passing: Peer-to-peer Communication



Example: [/gs/hs1/tga-ppcomp/23/test-mpi/](https://github.com/tga-ppcomp/23/test-mpi/)

Rank 0 computes contents of “`int a[16]`”

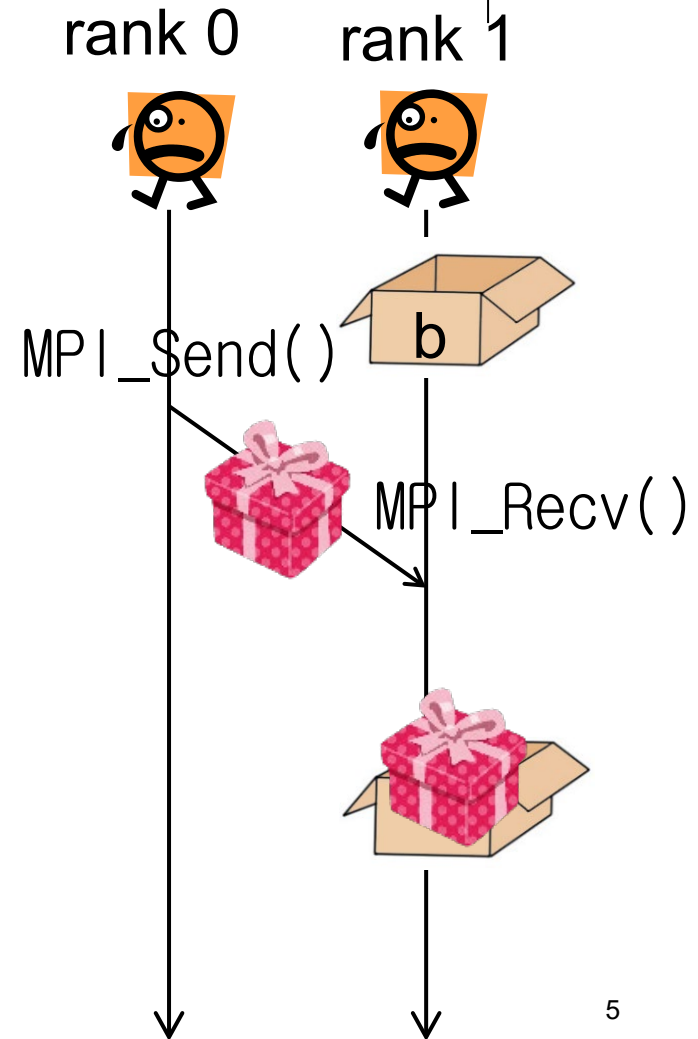
Rank 1 wants to see contents of `a`!

Rank0:

- Write data to an array `a`
- `MPI_Send(a, 16, MPI_INT, 1, 100, MPI_COMM_WORLD);`

Rank1:

- Prepares a memory region (array `b` here)
- `MPI_Recv(b, 16, MPI_INT, 0, 100, MPI_COMM_WORLD, &stat);`
- Now `b` has copy of `a` !





MPI_Send

```
MPI_Send(a, 16, MPI_INT, 1, 100, MPI_COMM_WORLD);
```

- **a**: Address of memory region to be sent
- **16**: Number of data to be sent
- **MPI_INT**: Data type of each element
 - MPI_CHAR, MPI_LONG, MPI_DOUBLE, MPI_BYTE...
- **1**: Destination process of the message
- **100**: An integer tag for this message (explained later)
- **MPI_COMM_WORLD**: Communicator (explained later)





MPI_Recv

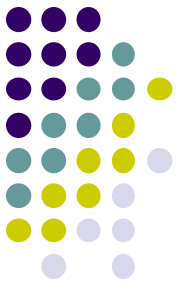
```
MPI_Status stat;
```

```
MPI_Recv(b, 16, MPI_INT, 0, 100, MPI_COMM_WORLD, &stat);
```

- **b**: Address of memory region to store incoming message
- **16**: Number of data to be received
- **MPI_INT**: Data type of each element
- **0**: Source process of the message
- **100**: An integer tag for a message to be received
 - Should be same as one in MPI_Send
- **MPI_COMM_WORLD**: Communicator (explained later)
- **&stat**: Some information on the message is stored

Note: MPI_Recv does not return until the message arrives

Notes on MPI_Recv: Message Matching (1)



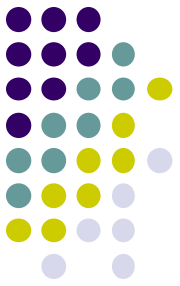
```
MPI_Recv(b, 16, MPI_INT, 2, 200, MPI_COMM_WORLD, &stat);
```



I only want a message with tag 200 from 2 !

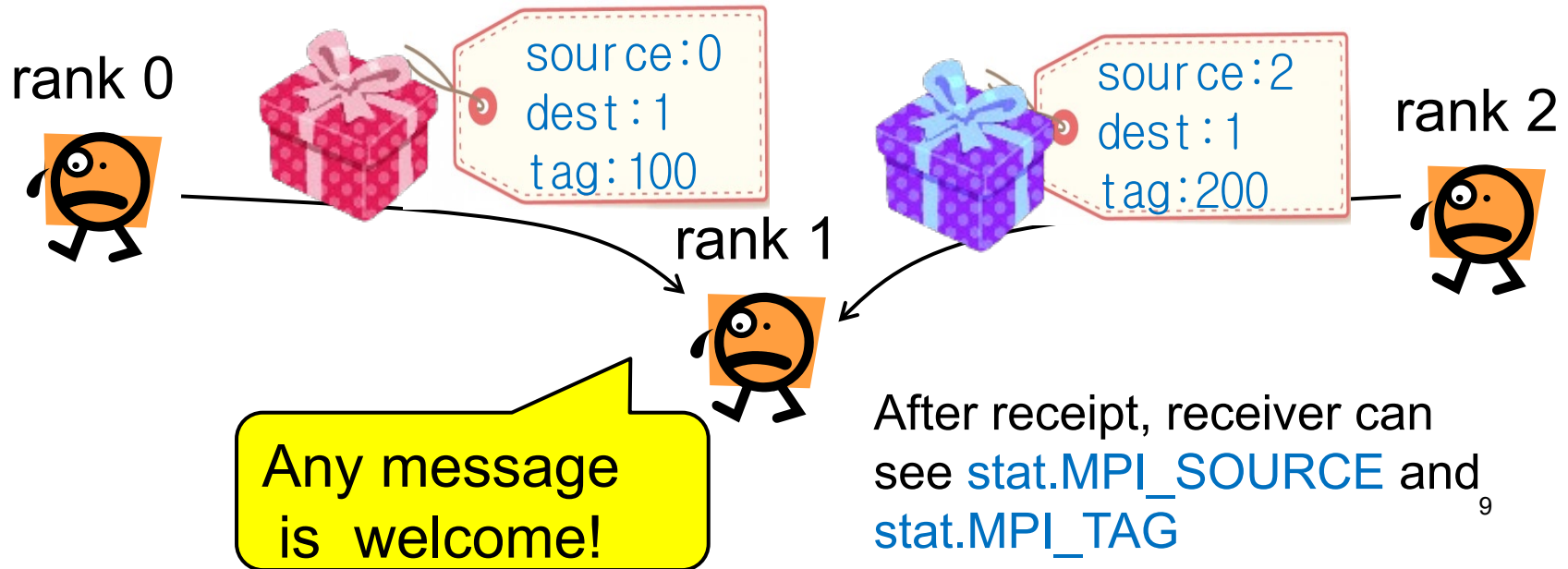
- Receiver specifies “source” and “tag” that it wants to receive
→ The message that **matches the condition** is delivered
- Other messages should be received by other MPI_Recv calls later

Notes on MPI_Recv: Message Matching (2)



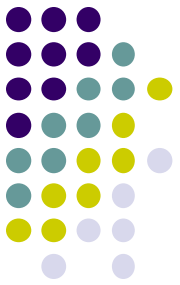
- In some algorithms, the sender may not be known beforehand
 - cf) client-server model
- For such cases, **MPI_ANY_SOURCE / MPI_ANY_TAG** may be useful

```
MPI_Status stat;  
MPI_Recv(b, 16, MPI_INT, MPI_ANY_SOURCE, MPI_ANY_TAG,  
MPI_COMM_WORLD, &stat);
```



Notes on MPI_Recv:

What If Message Size is Unmatched

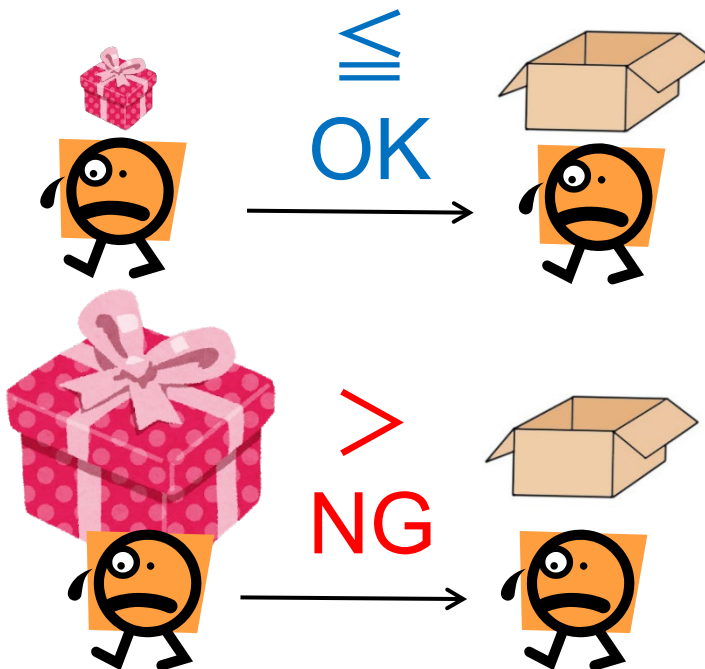


```
MPI_Recv(b, 16, MPI_INT, 0, 100, MPI_COMM_WORLD, &stat);
```

If message is **smaller** than expected, it's **ok**

→ Receiver can know the actual size by

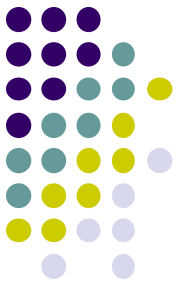
```
MPI_Get_Count(&stat, MPI_INT, &s);
```



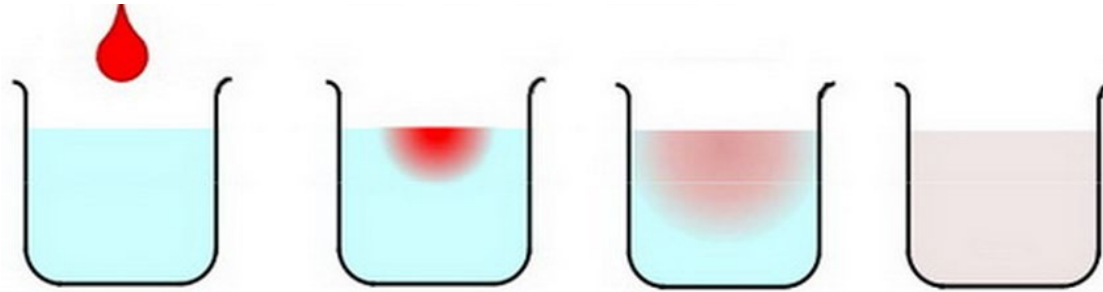
If message is **larger** than expected, it's **an error** (the program aborts)

If the message size is UNKNOWN beforehand, the receiver should prepare enough memory

Case of “diffusion” Sample related to [M1]



An example of diffusion phenomena:



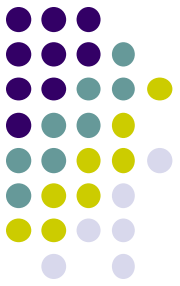
The ink spreads gradually, and finally the density becomes uniform (Figure by Prof. T. Aoki)

Available at </gs/bs/tga-ppcomp/24/diffusion/>

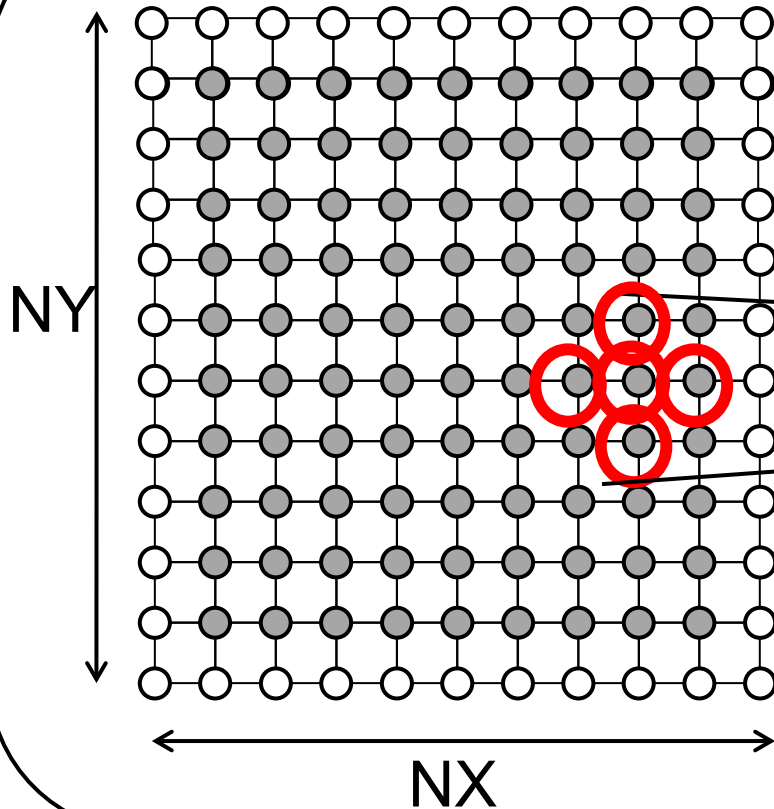
- Execution: `./diffusion [nt]`
 - nt: Number of time steps

You can use </gs/bs/tga-ppcomp/24/diffusion-mpi/> as a base. Makefile uses mpicc

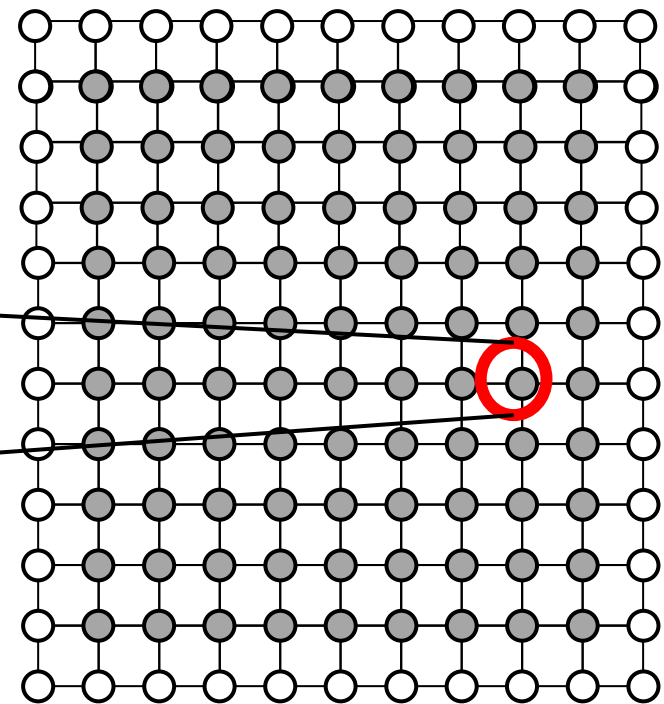
Data Structure in Original “diffusion”



An Array for “even” steps



An Array for “odd” steps



How can we distribute data?

How Do We Parallelize “diffusion” Sample?



On OpenMP:

[Algorithm] Parallelize spatial (Y or X) for-loop

- Each thread computes its part in the space
- Time (T) loop cannot be parallelized, due to dependency

[Data] Data structure is same as original:

- 2 x 2D arrays → `float data[2][NY][NX];`

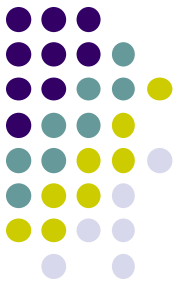
On MPI:

[Algorithm] Same as above

- Each process computes its part in the space

[Data] 2 x 2D arrays are divided among processes

- Each process has its own part of arrays

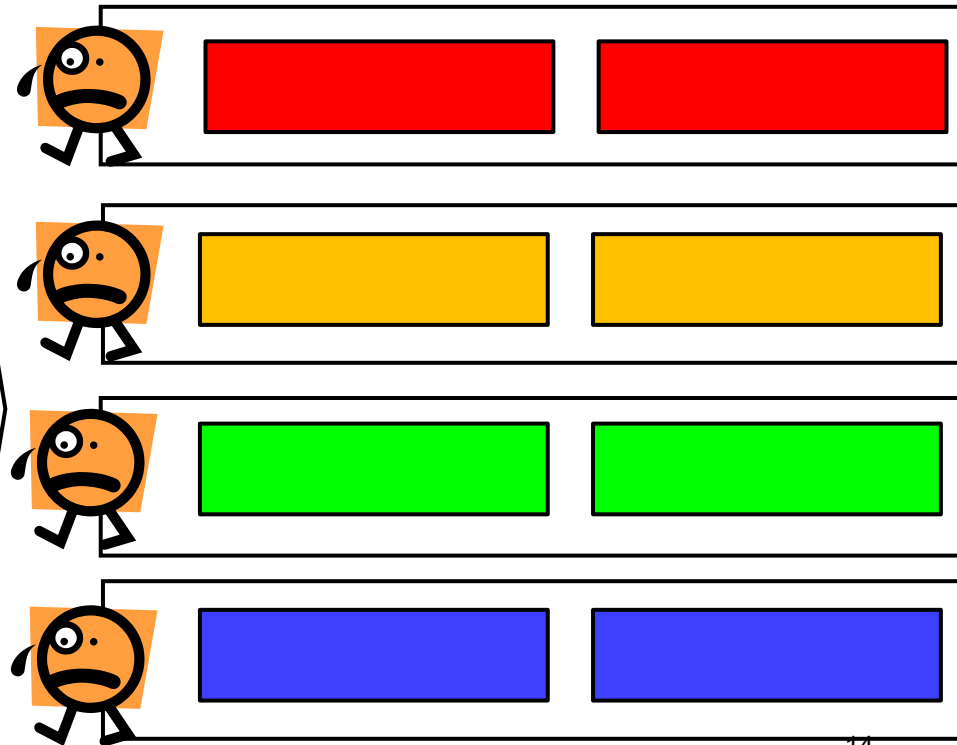
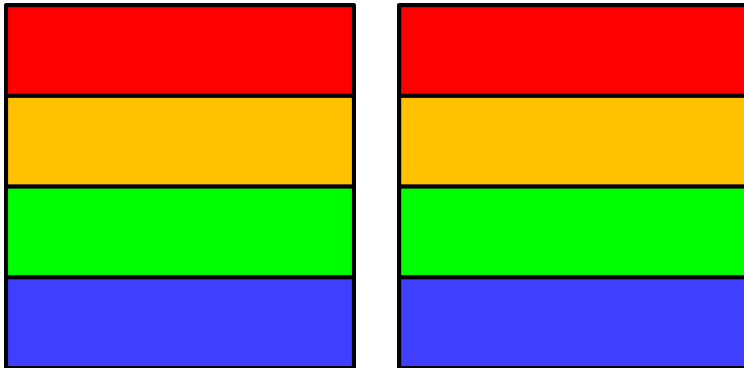


Considering Data Distribution (1)

2 x 2D arrays are divided among
P processes (in this case, horizontally)



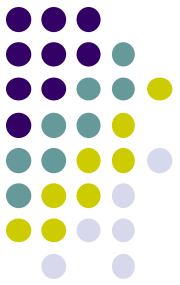
✂ A color = a process



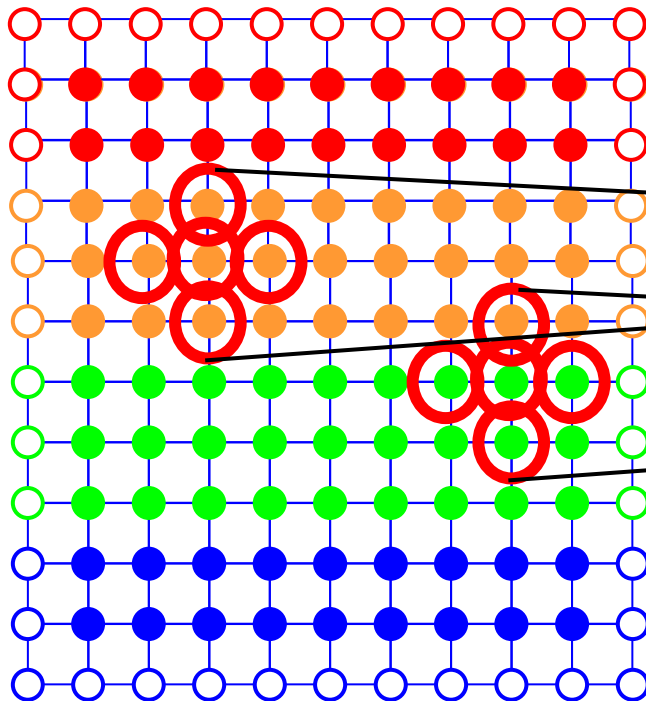
This looks ok, but will be
improved next

Each array size is (roughly)
 $NX \times (NY/P)$

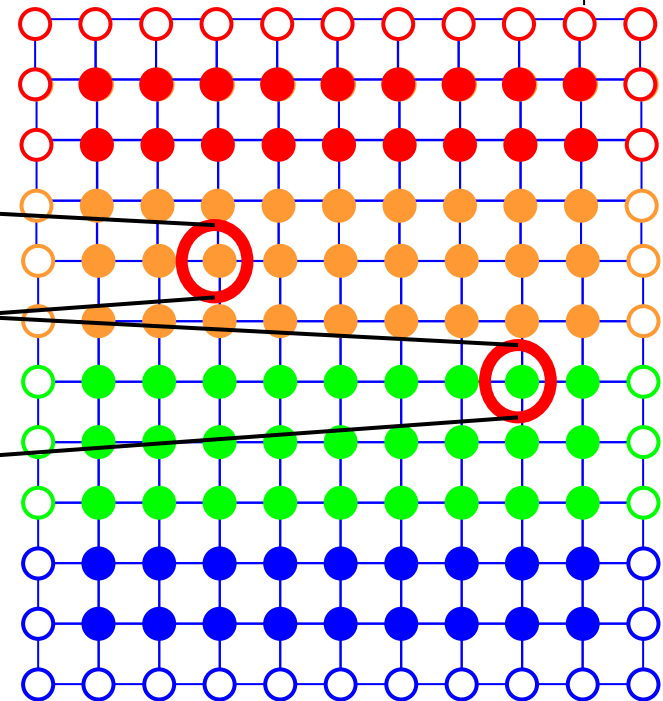
Improving Data Distribution (1)



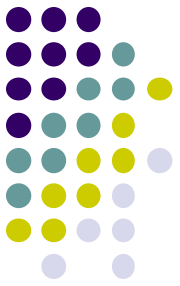
An Array for “even” steps



An Array for “odd” steps

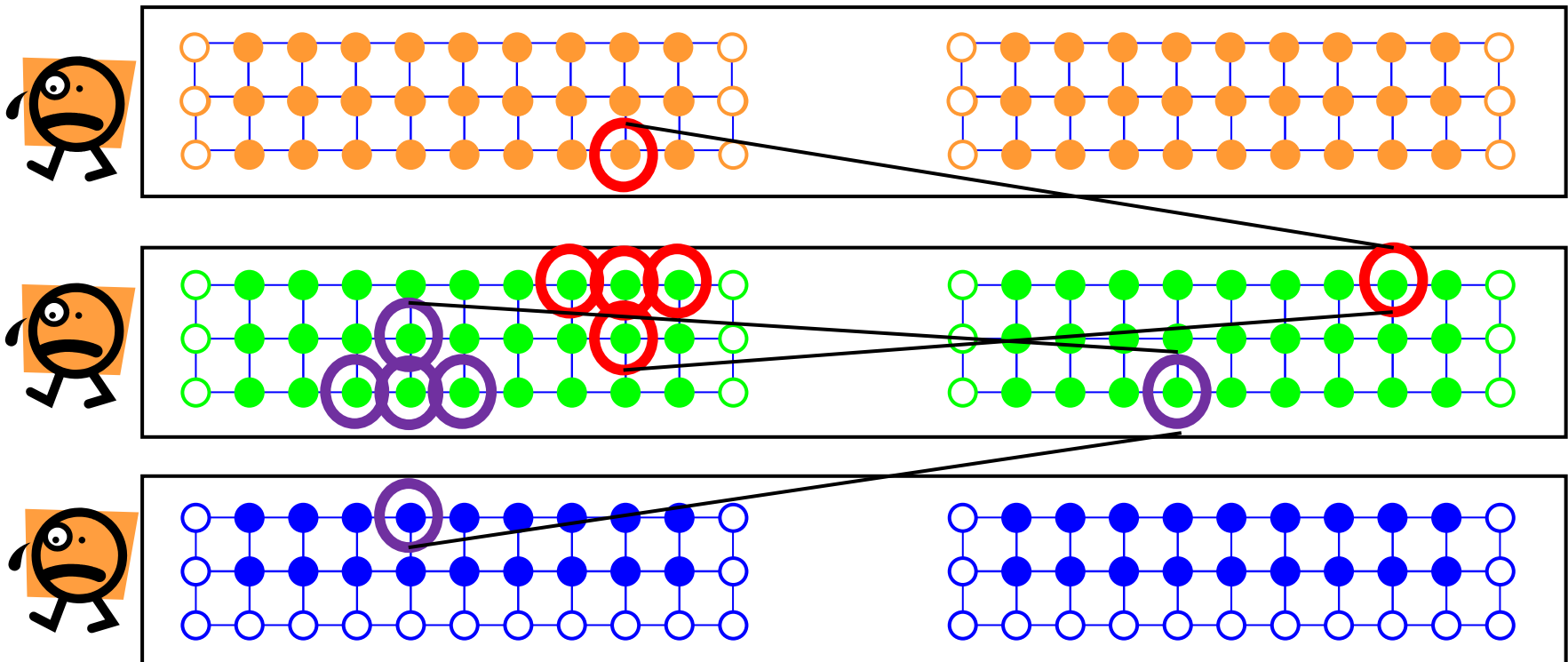


- Let's remember computation of each point
→ 5 points are read and 1 point is written



Improving Data Distribution (2)

- What's wrong with the simple distribution?



Computation requires data in other processes

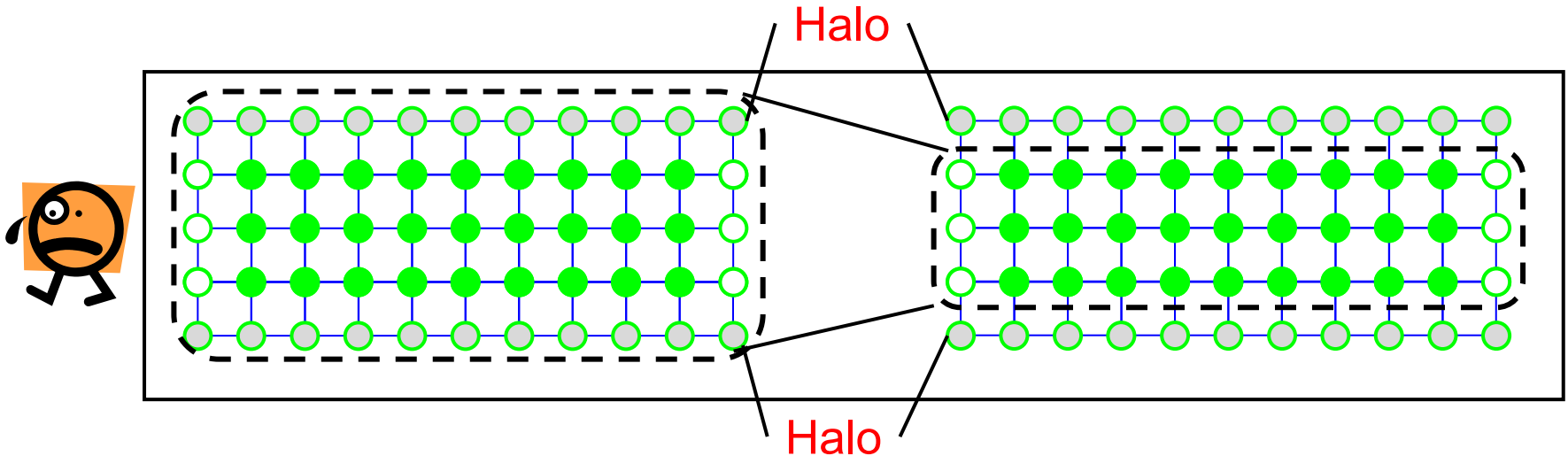
→ **Message passing is required**

We need memory region for received data!

A Technique in Stencil: Introducing “Halo” Region

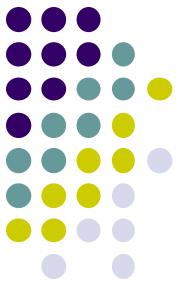


- In stencil computation, it is a good idea to make additional rows to arrays
→ called “Halo” region



Each array size is (roughly) $NX \times (NY/P + 2)$

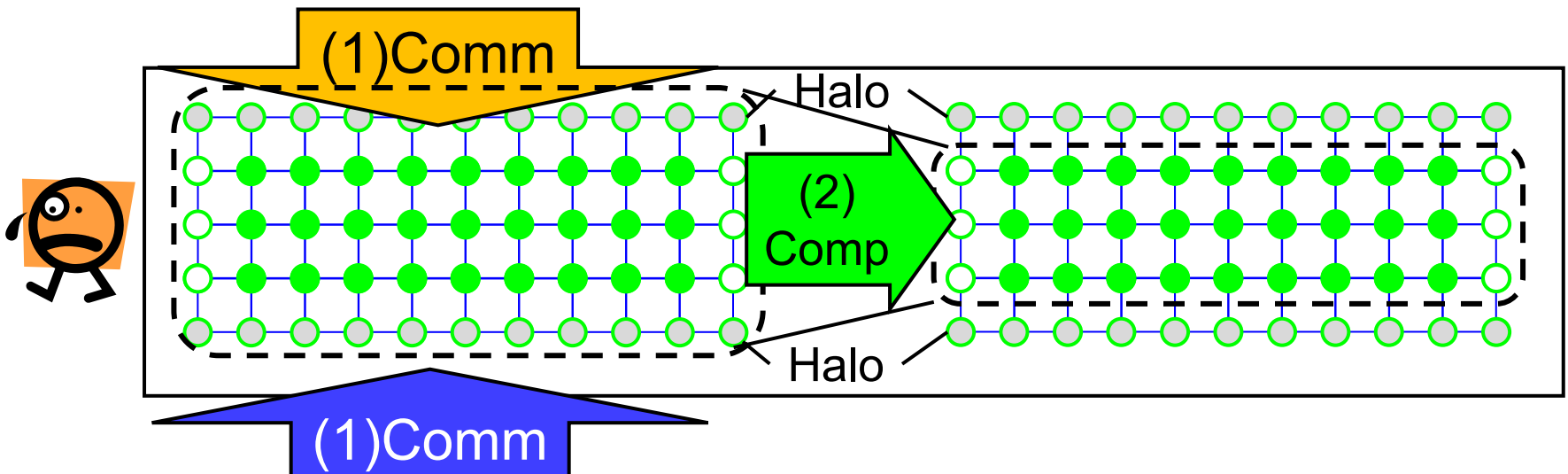
Halo regions are used to **receive** outside border data
from neighbor processes



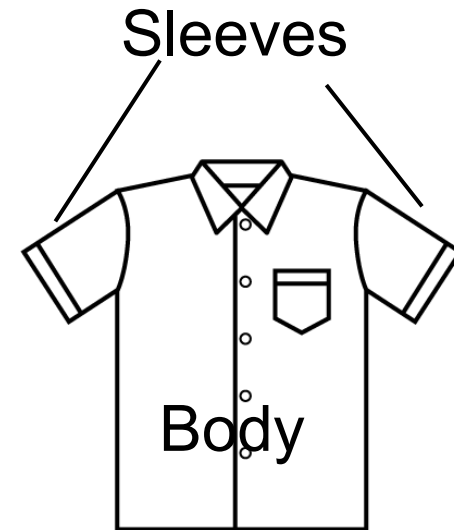
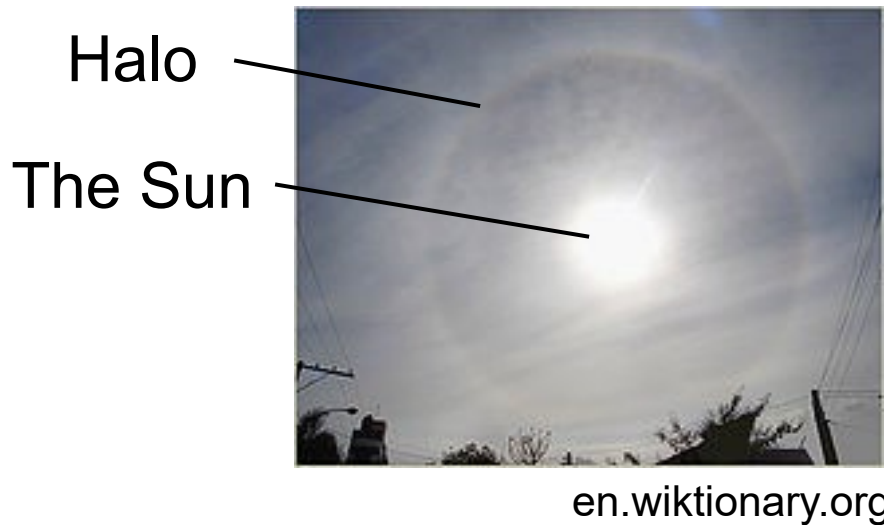
Using “Halo” Region

Each time step consists of:

- (1) **Communication**: Recv data and store into “halo” region
 - Also neighbor processes need “my” data
- (2) **Computation**: Old data at time t (including “halo”)
→ New data at time $t+1$



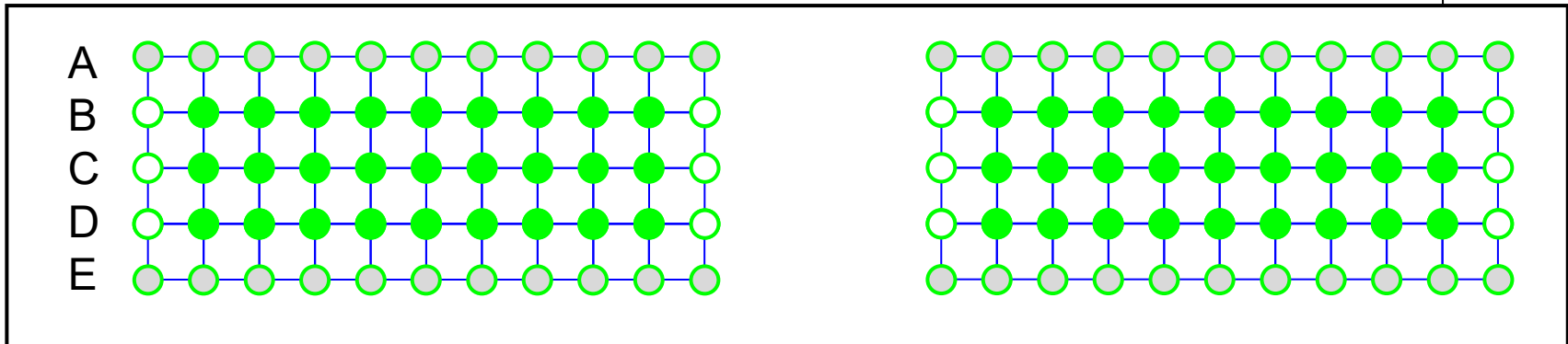
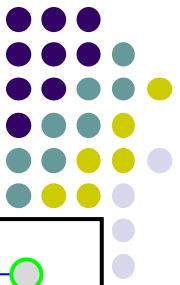
The name of “Halo” Region



© dak

“Halo regions” are sometimes called “sleeve regions” or “overlap regions”

Overview of MPI “diffusion”



```
for (t = 0; t < nt; t++) {
```

```
    if (rank > 0) Send B to rank-1
```

```
    if (rank < size-1) Send D to rank+1
```

```
    if (rank > 0) Recv A from rank-1
```

```
    if (rank < size-1) Recv E from rank+1
```

(1) Communication
in “old” array

```
    Computes points in rows B-D
```

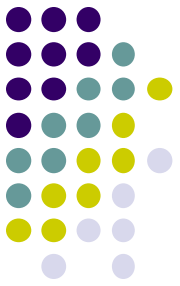
```
    Switch old and new arrays
```

(2) Computation
“old” array \Rightarrow “new” array

```
}
```

This version is still unsafe, for possibility of **deadlock**
→ Explained next

A Sample with Neighbor Communication

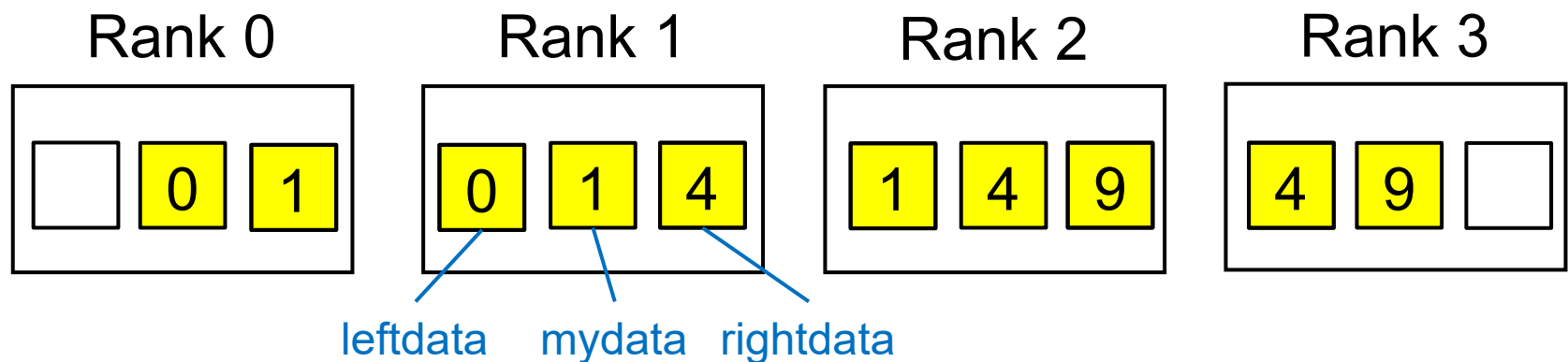


When considering neighbor communication, we have to avoid deadlock (a serious bug)!

A sample is available at [/gs/bs/tga-ppcomp/24/neicomm-mpi](https://github.com/tga-ppcomp/24/neicomm-mpi)

Execution: `mpiexec -n [P] ./neicomm`

- (1) Each process prepares its local data
- (2) Each process receives data from its neighbors, rank-1 and rank+1



(actually each of them is an array)



neicomm-mpi sample

- `/gs/bs/tga-ppcomp/24/neicomm-mpi`
- The behavior is different with different MPI libraries. We use “openmpi” here, different from usual

```
[make sure that you are at a interactive node (rXn11) ]  
module purge [Clear loaded modules]  
module load openmpi [Do once after login]  
cd ~/ppc24  
cp -r /gs/bs/tga-ppcomp/24/neicomm-mpi .  
cd neicomm-mpi  
[See main() in neicomm.c. Which is called, neicomm_safe() or  
neicomm_unsafe()?]  
make  
[An executable file “neicomm” is created]  
mpiexec -n 4 ./neicomm
```

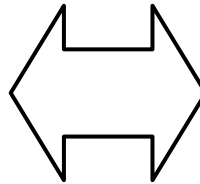


Behavior of neicomm-mpi Sample

Unsafe version ☹️

When `neicomm_unsafe()`
is used

```
Send to rank-1  
Send to rank+1  
Recv from rank-1  
Recv from rank+1
```



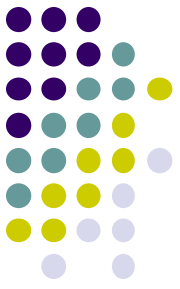
Safe version 😊

When `neicomm_safe()`
is used

```
Start to recv from rank-1  
Start to recv from rank+1  
Sent to rank-1  
Sent to rank+1  
Finish to recv from rank-1  
Finish to recv from rank+1
```

❌ The sample may not finish
due to “deadlock”.

To abort it, press Ctrl+C



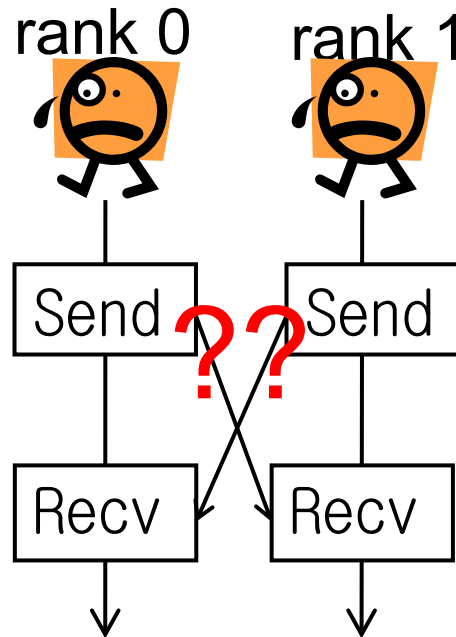
Cautions with neicomm sample

- On an interactive node, we can see the anomaly and stop the execution with “Ctrl+C”.
- But how about with job scheduler?
- ➔ We cannot see the anomaly. The job may use up time limit, with “-l h_rt=...”.
- The behavior differs with different MPI libraries
- With intel-mpi, we may see problem only with very large N, such as $(64 \times 1024 \times 1024)$



Deadlock in MPI

- This case “deadlocks” with 2 processes. Why?



One of reasons is usual **MPI_Send** and **MPI_Recv** uses “**blocking communication**”

- a process waits until “some event”

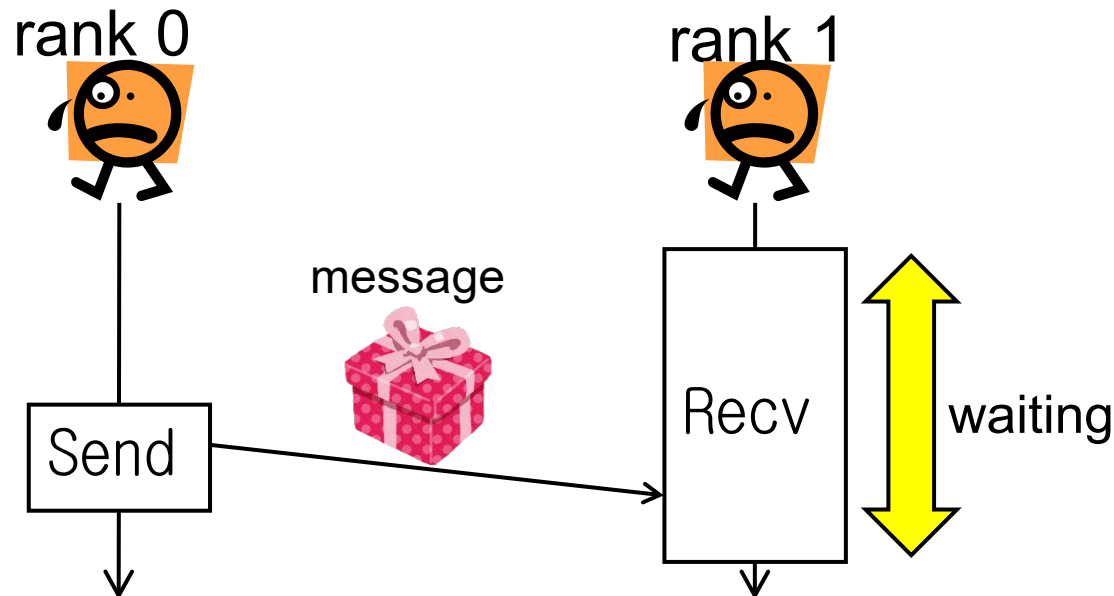


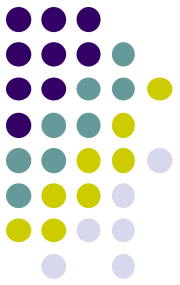
Behavior of MPI_Recv()

- MPI_Send is called by rank0, and MPI_Recv is called on rank1
 - Processes are running independently

If MPI_Recv is called earlier,

→ MPI_Recv() waits until the message arrives (**blocking**)

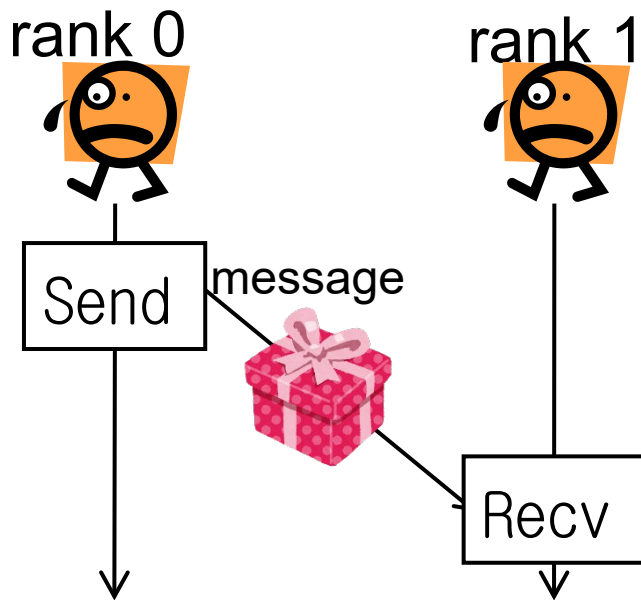




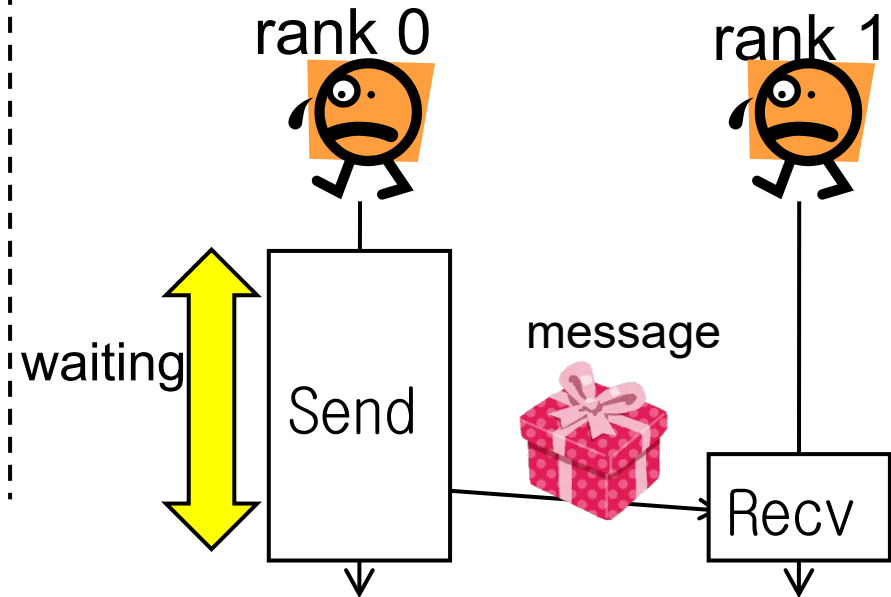
Behavior of MPI_Send()

If MPI_Send is called earlier, there are two possibilities

(case 1) MPI_Send() finishes soon (**non-blocking**)

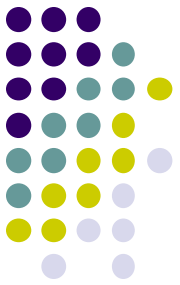


(case 2) MPI_Send() waits until the message arrives to destination (**blocking**)



Which occurs?

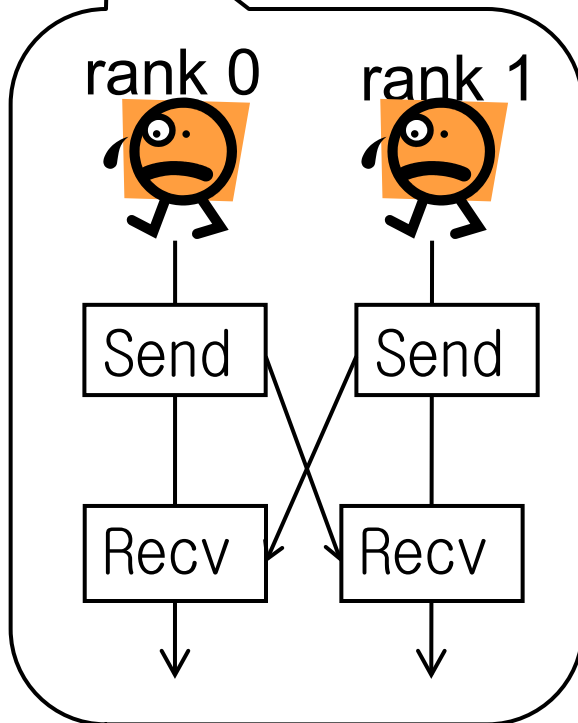
It depends on MPI library, message size, etc. → **Unknown**



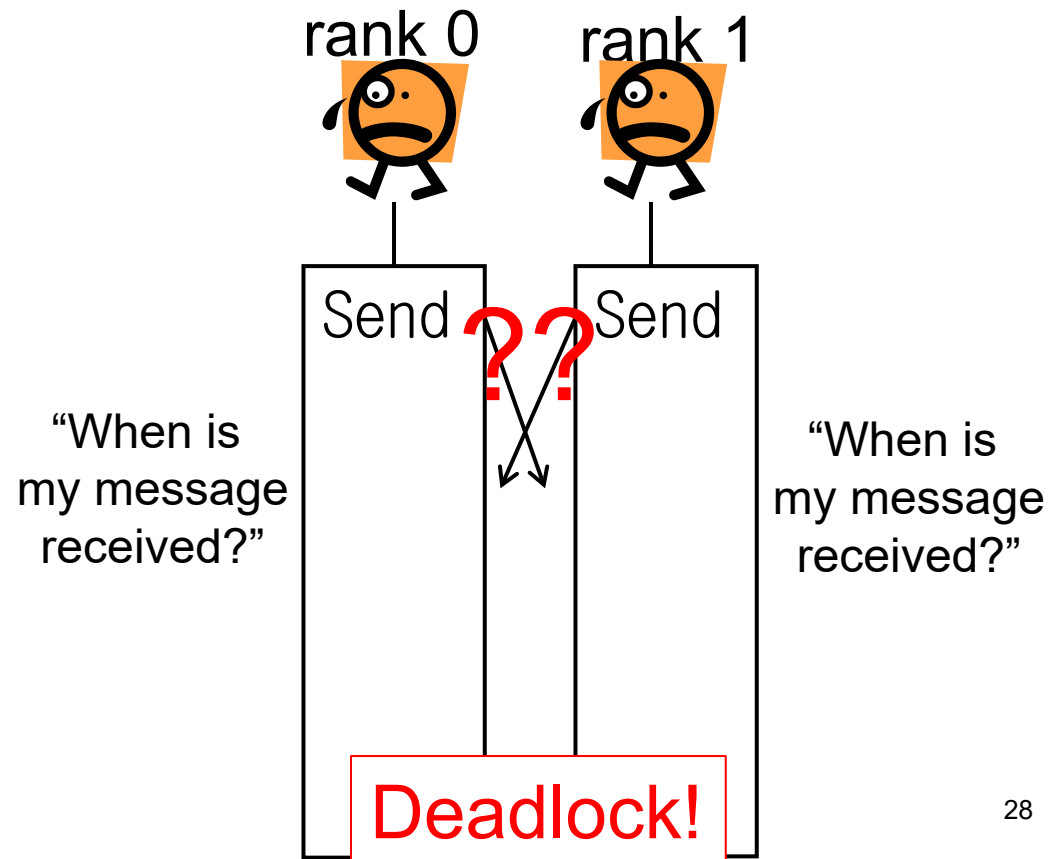
And Deadlock Happens



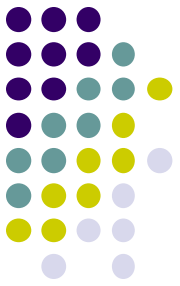
? Programmer's expectation



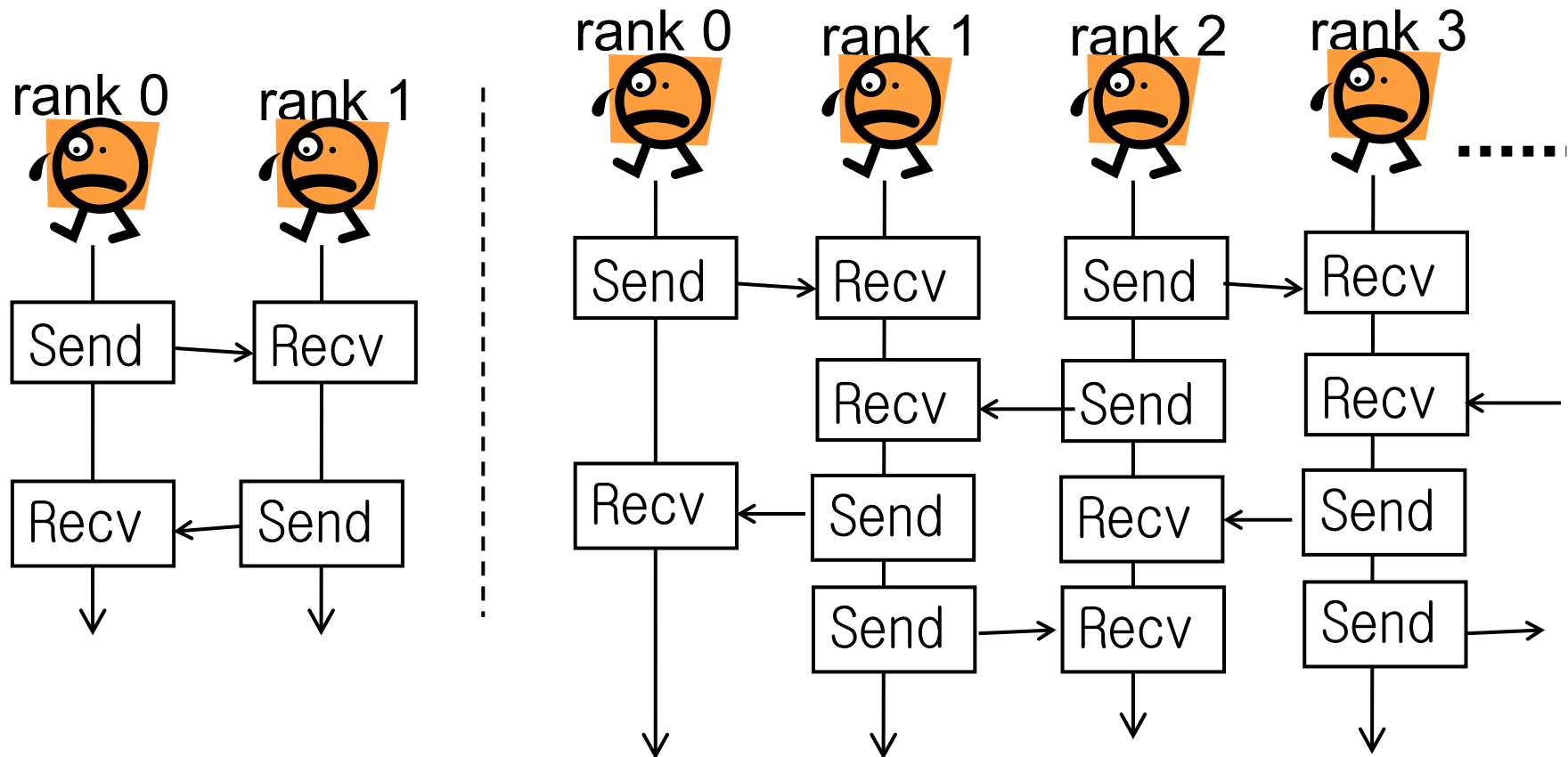
If MPI_Send is blocked until arrival in destination ...



One of Approaches to Avoid Deadlock



- To change order of MPI_Send and MPI_Recv

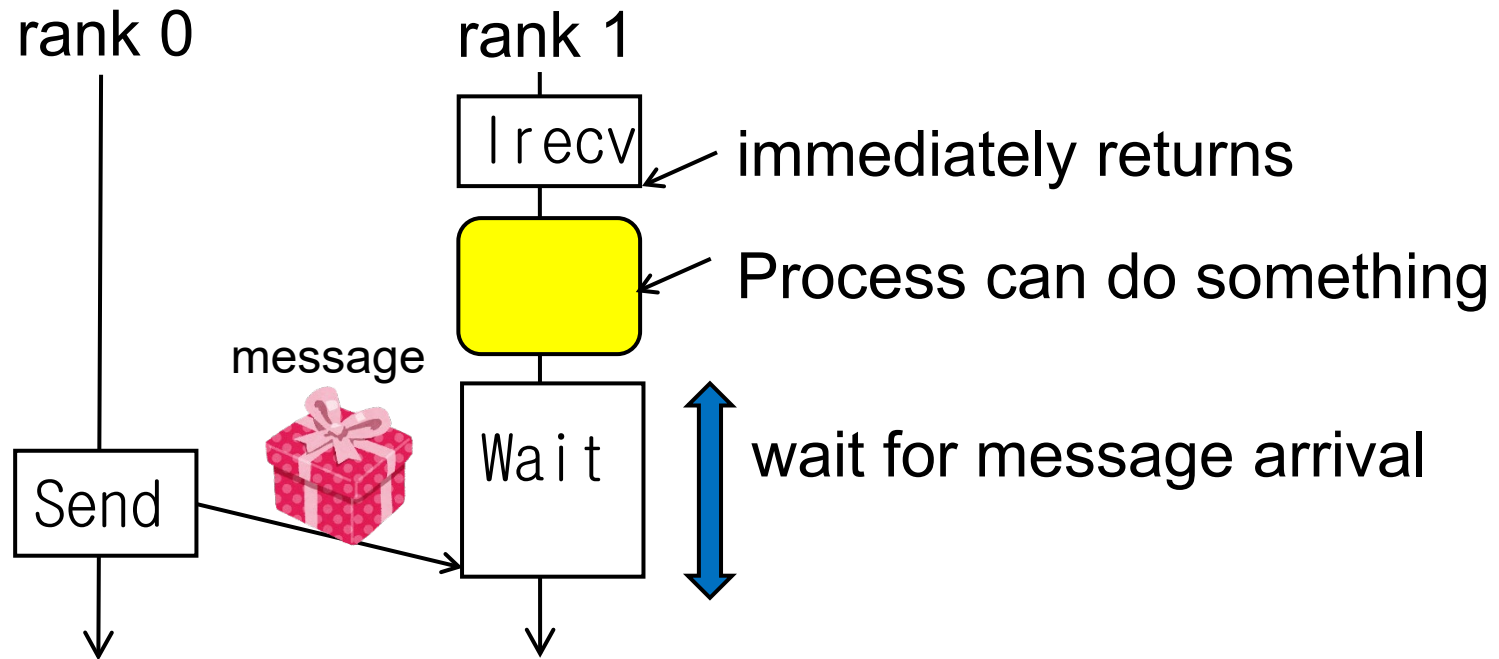


Even processes and odd processes work differently
We will another approach

Another Approach: Using Non-Blocking Communication



- **Non-blocking communication**: starts a communication (send or receive), but does **not wait** for its completion
 - MPI_Recv is **blocking communication**, since it waits for message arrival
- Program must wait for its completion later: **MPI_Wait()**





Non-Blocking Receive

```
MPI_Status stat;  
MPI_Recv(buf, n, type, src, tag, comm, &stat);
```



```
MPI_Status stat;  
MPI_Request req;  
MPI_Irecv(buf, n, type, src, tag, comm, &req); ←start recv  
    : (Do something)  
MPI_Wait(&req, &stat); ←wait for completion
```

MPI_Irecv: starts receiving, but it returns **I**mmediately

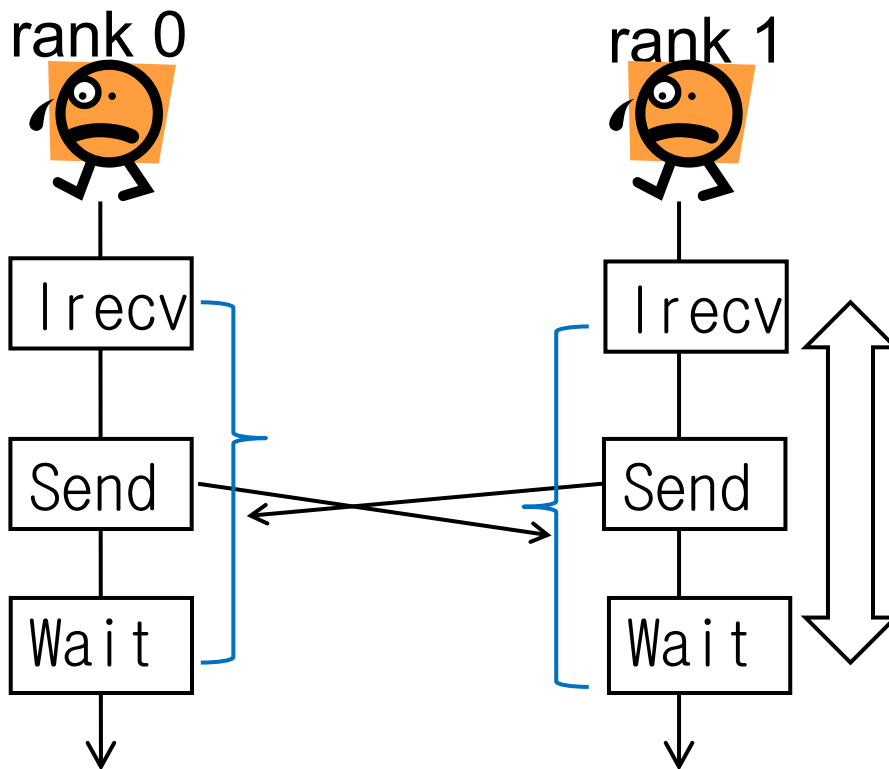
MPI_Wait: wait for message arrival

MPI_Request is like a “ticket” for the communication

Avoiding Deadlock with Non-Blocking Communication



On each process, Recv is divided into Irecv & Wait



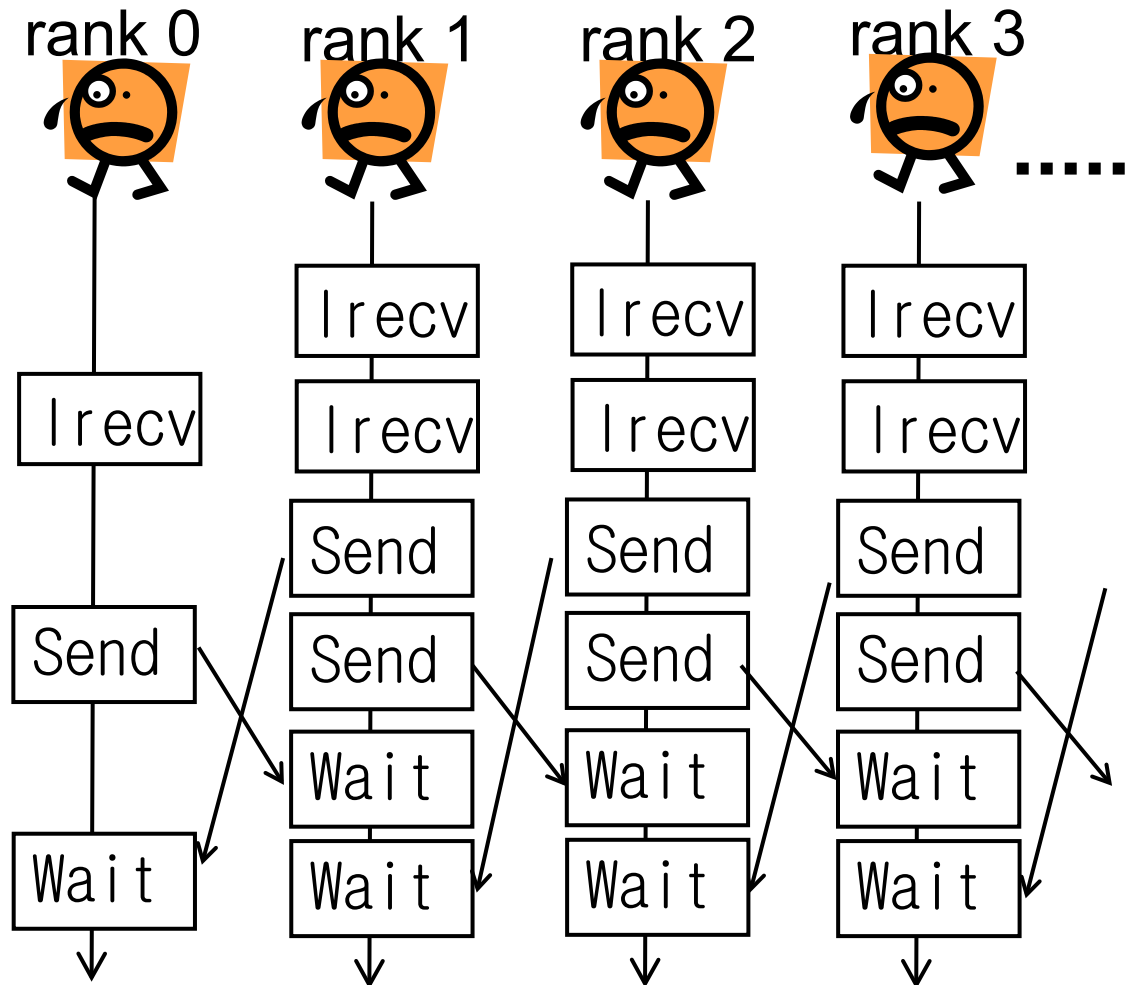
What's difference than before?

A message can be (internally) received during Irecv and Wait
→ MPI_Send can finish in finite time



Cases for Multiple Processes

- See `neicomm_safe()` in `neicomm.c`



Each lrecv
has to use
distinct
MPI_Request

Functions Related to Non-blocking Communication



- `MPI_Isend(buf, n, type, dest, tag, comm, &req);` ←start send
 - `MPI_Isend` must be followed by `MPI_Wait` (or alternatives)
- `MPI_Wait(&req, &stat);` ←wait for completion of one communication
- `MPI_Test(&req, &flag, &stat);` ←check completion of one communication
- `MPI_Waitall`, `MPI_Waitany`, `MPI_Testall`, `MPI_Testany`...

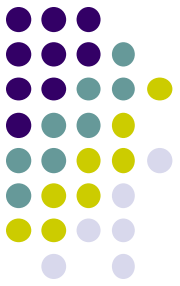
Avoiding Deadlock with Non-Blocking Communication (2)



- The following patterns are also Ok
- Each process does
 - Irecv, Irecv, Send, Send, Wait, Wait
 - Use in `neicomm_safe()`
 - Isend, Isend, Recv, Recv, Wait, Wait
 - Isend, Isend, Irecv, Irecv, Wait, Wait, Wait, Wait
 - 4 `MPI_Request` required
 - Irecv, Irecv, Send, Send, Wait, Wait, Wait, Wait
 - 4 `MPI_Request` required

“Send, Send, Irecv, Irecv, Wait, Wait” is NG. Why?

Assignments in MPI Part (Abstract)



Choose one of [M1]—[M3], and submit a report
Due date: **June 14 (Thursday)**

[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



Next Class

- MPI (3)
 - Improvement of “matrix multiply” sample
 - Related to [M2]
 - Group Communication
- Planned schedule
 - May 30: Part 3 (3)
 - June 3: Part 3 (4): (Short) class + TSUBAME4 tour
 - If you come to G2-202, Suzukake-dai, you can see TSUBAME4