CME 213

SPRING 2017

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MVAPICH library

- mvapich2/2.3a-intel-16 on Certainty currently has a bug that prevents `mpirun` from working on more than 24 processes.
- Use mvapich2/2.2b-intel-16 instead to run on more than 24 processes.
- However, only mvapich2/2.3a has CUDA support. `nvprof` needs CUDA support.
- You can also use `mpirun_rsh` with mvapich2/2.3a.

Process mapping

- It is important to control the binding and mapping of the processes.
- How do you map processes to nodes?
- Binding: which hardware thread runs a process is controlled by the OS. Should a process be run by?
  - a specific hardware thread
  - any hardware thread on a core
  - any hardware thread on a socket
  - any hardware thread on a NUMA domain
- Mapping: a thread is assigned to which resource on a node, e.g., which socket?

Why mapping? Optimization!

- Mapping of processes is important.
- You may want to use many nodes to use more memory.
- You may want to have all threads on the same socket for faster shared memory access.
- You may want to have threads on different sockets to better utilize the memory buses.
- You may want to have as many processes per node as the number of GPU processors.
- You may want to use OpenMP with your MPI code.

Number of processes and nodes to use

```
#PBS -l nodes=4:ppn=24
```

Reserving 4 nodes, each with 24 hardware threads.

```
mpiexec -np 96 -ppn 24 ./mpi_hello
```

Create 96 processes, with 24 processes per node.

```
mpiexec -np 16 -ppn 4 ./mpi_hello
```

Create 16 processes, with 4 processes per node.

Process binding

- OS is responsible for assigning a hardware thread to each process.
- How do you control this mapping?

`-bind-to object`

- Specify the size of the hardware element to restrict each process to.

- This determines how the OS can migrate a process. Does the process stay with the same hardware thread or is it allowed to migrate to another thread (say on the same socket)?

-bind-to

Options are [`mpiexec -bind-to –help`]

`numa`	bind to numa domain
`socket`	bind to socket
`core`	bind to core
`hwthread`	bind to hardware thread
`l1cache`	bind to process on L1 cache domain
`l2cache`	bind to process on L2 cache domain
`l3cache`	bind to process on L3 cache domain

map-by

`map-by object`

Skip over object between bindings.

Options are the same as `bind-to`.

Usage example:

```
mpiexec -bind-to hwthread -map-by socket -np 4 -ppn 4 ./a.out
```

Add

```
HYDRA_TOPO_DEBUG=1 mpiexec …
```

for DEBUG information.

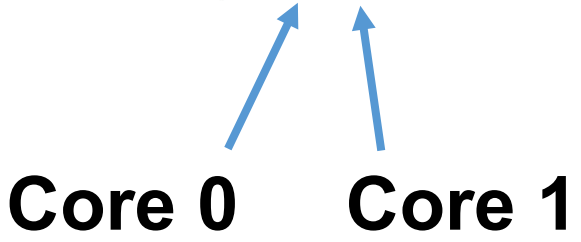
Map by socket

```
mpiexec -bind-to hwthread -map-by socket
process 0 binding: 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 1 binding: 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 2 binding: 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0
process 3 binding: 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0
```

Socket 0 **Socket 1**

Map by core

```
mpiexec -bind-to hwthread -map-by core
process 0 binding: 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 1 binding: 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 2 binding: 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 3 binding: 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```



Map by hardware thread

```
mpiexec -bind-to hwthread -map-by hwthread
process 0 binding: 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 1 binding: 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0
process 2 binding: 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
process 3 binding: 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0
```

Core 0 Thread 0

Core 0 thread 1

Bind to socket

```
mpiexec -bind-to socket -map-by socket
process 0 binding: 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0
process 1 binding: 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1
process 2 binding: 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0
process 3 binding: 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1
```

Spread processes across sockets

```
mpiexec -bind-to socket -map-by core
process 0 binding: 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0
process 1 binding: 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0
process 2 binding: 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0
process 3 binding: 1 1 1 1 1 1 0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0 0 0
```

Bunch processes inside each socket

have a memory intensive appli
at requires 4 processes, would you pla
the 4 processes

on the same socket?

on different sockets?

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have 4 processes that require a ter-process communication, would yo place them on

different sockets?

the same ocket?

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u are running on a node that is
with other processes (OS, MPI, etc), is i
better to

bind a process to a hardware thread?

bind a process to a socket?

not specify any binding?

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ou want to run a program with 2 rocesses that requires 25 GB of memo per process, on computer nodes with 24 hardware threads and 64 GB of memory. How many processes would you assign per node?

1

2

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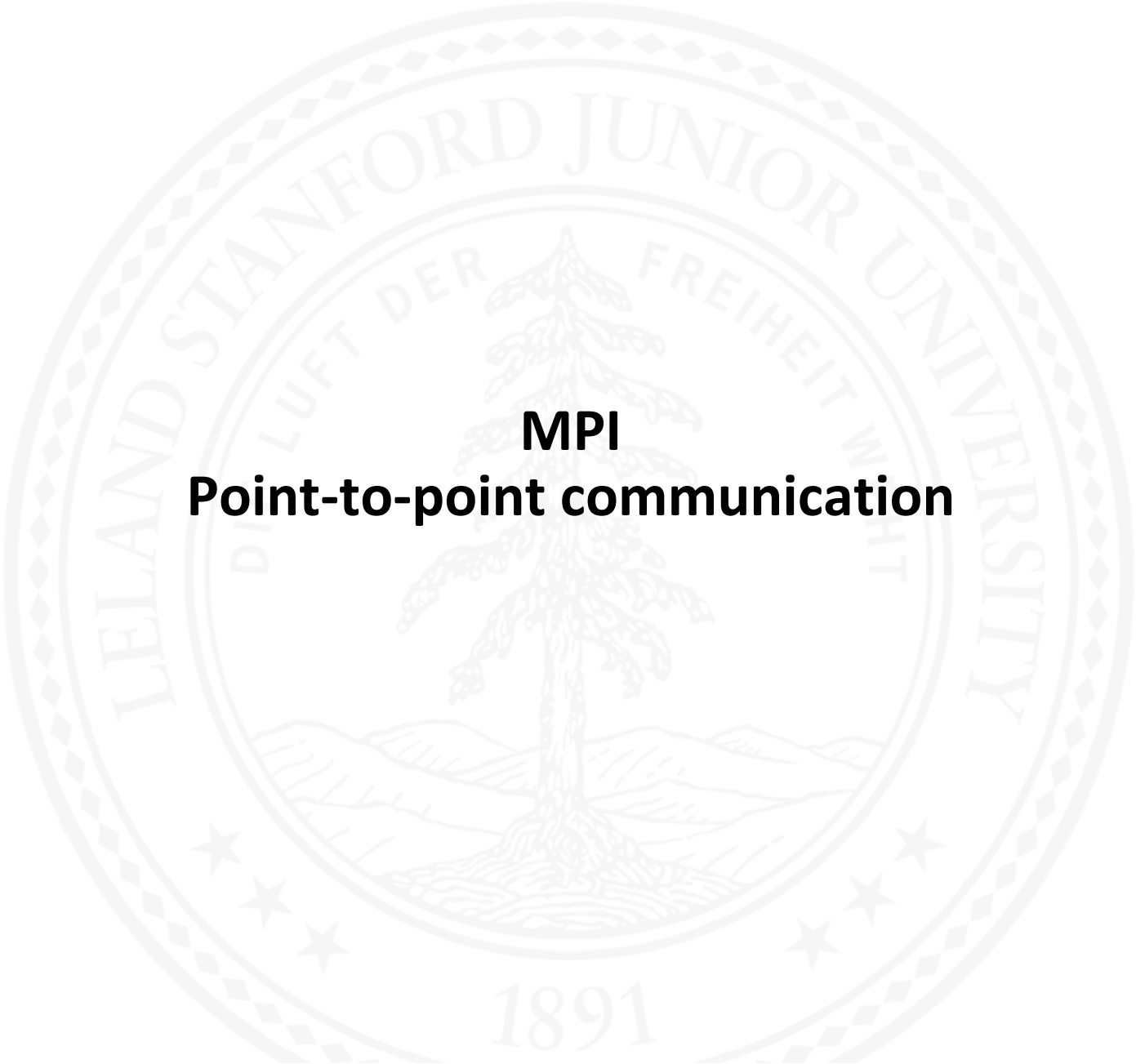


MPI
Point-to-point communication

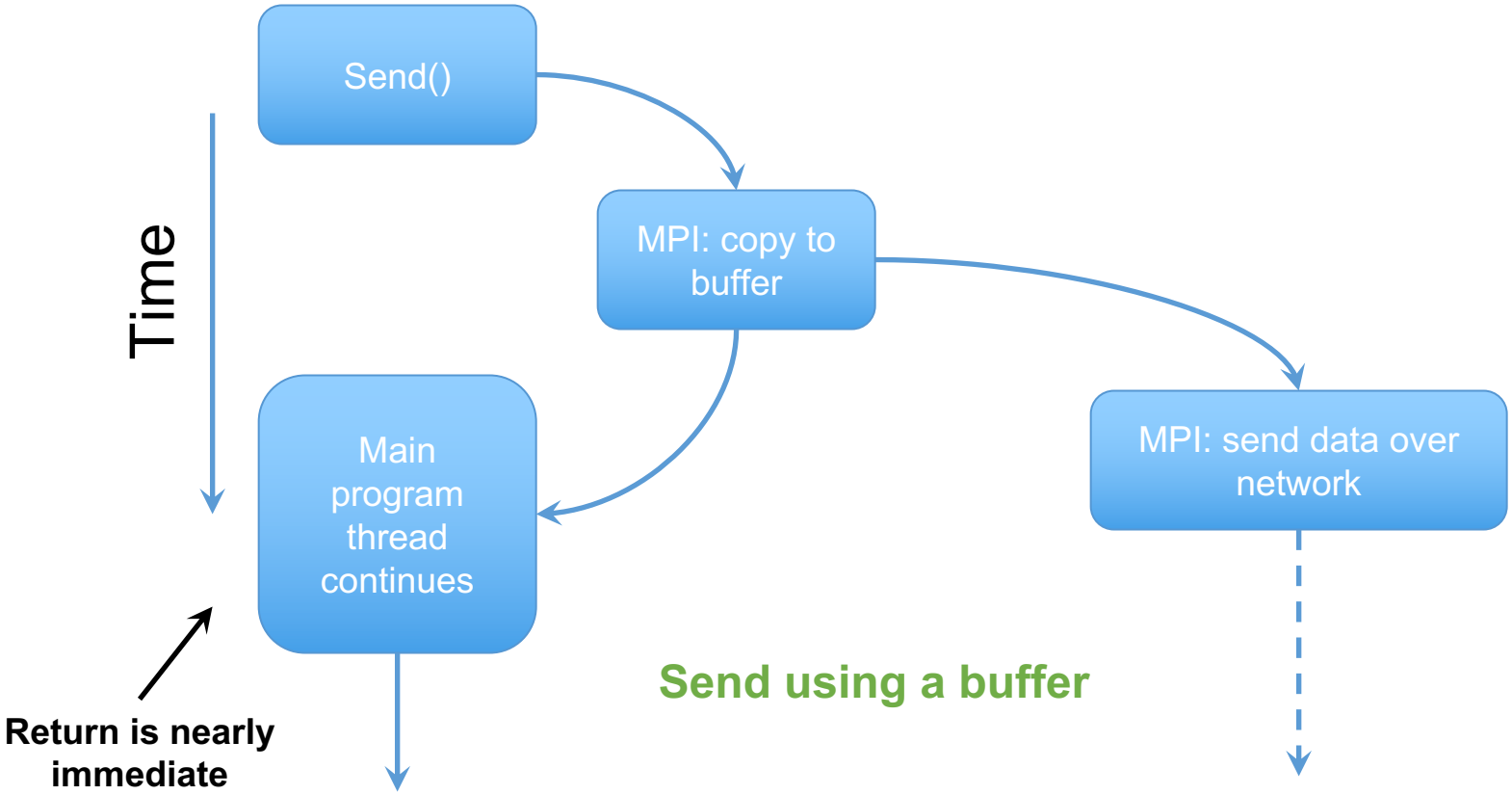
Point-to-point communication

- There are a few technical details to understand regarding communication.
- This is important to understand whether a deadlock may occur in your program or not.
- Two main concepts:
  - Blocking/non-blocking
  - Synchronous/asynchronous (not common in practice)

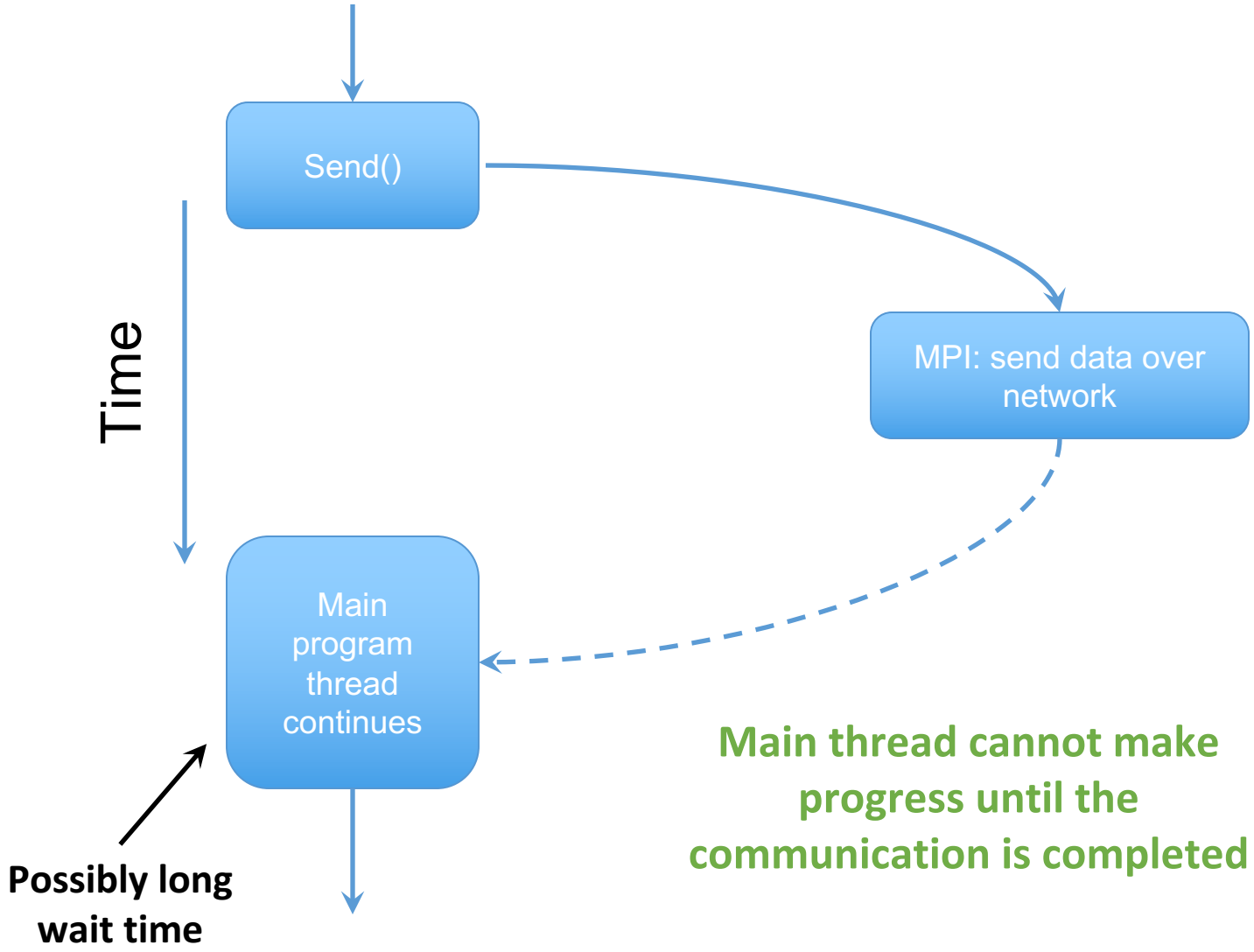
Two ways to communicate

1) using an MPI system buffer

To optimize the communication the MPI library uses two different strategies for communication: buffered and non-buffered.

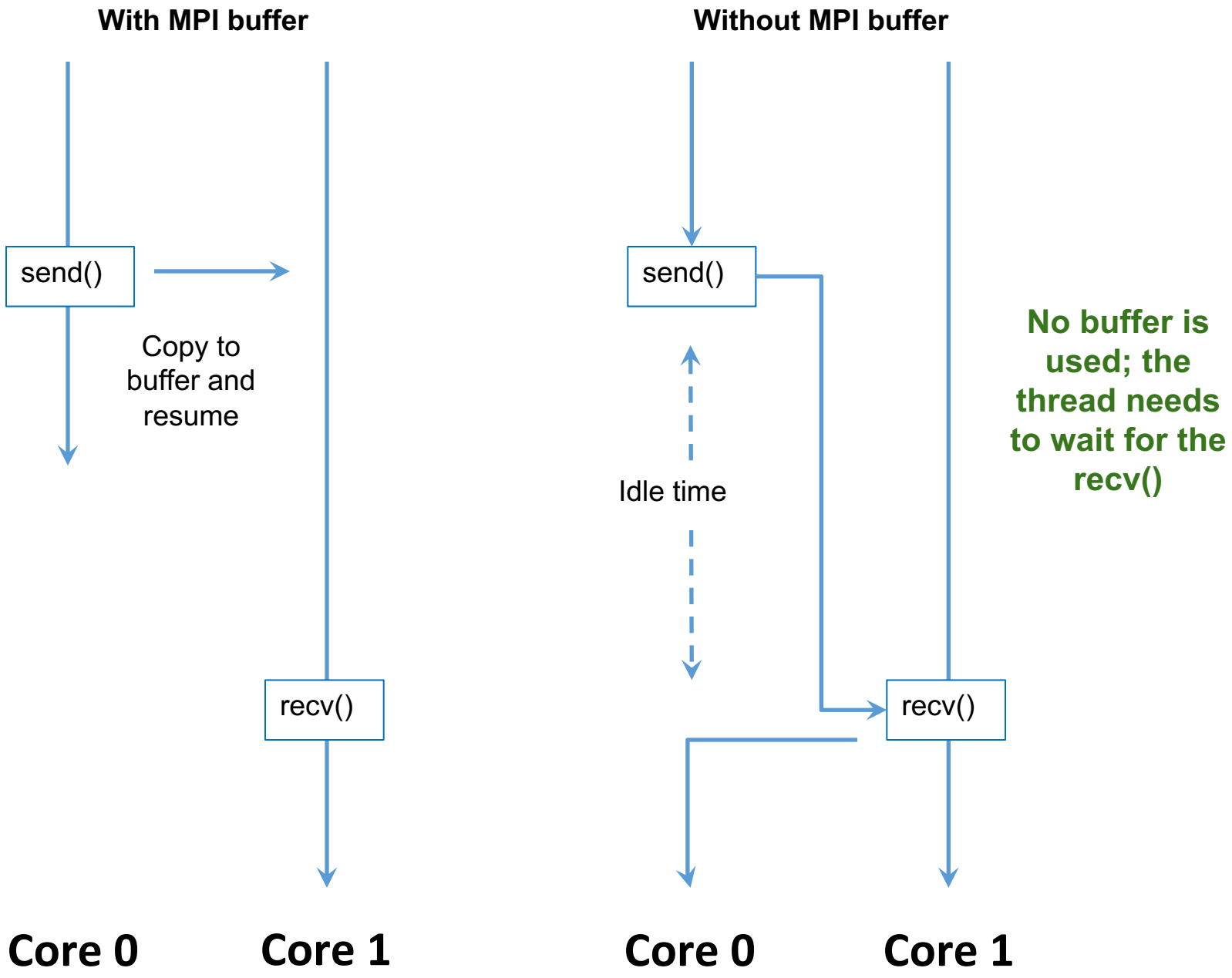


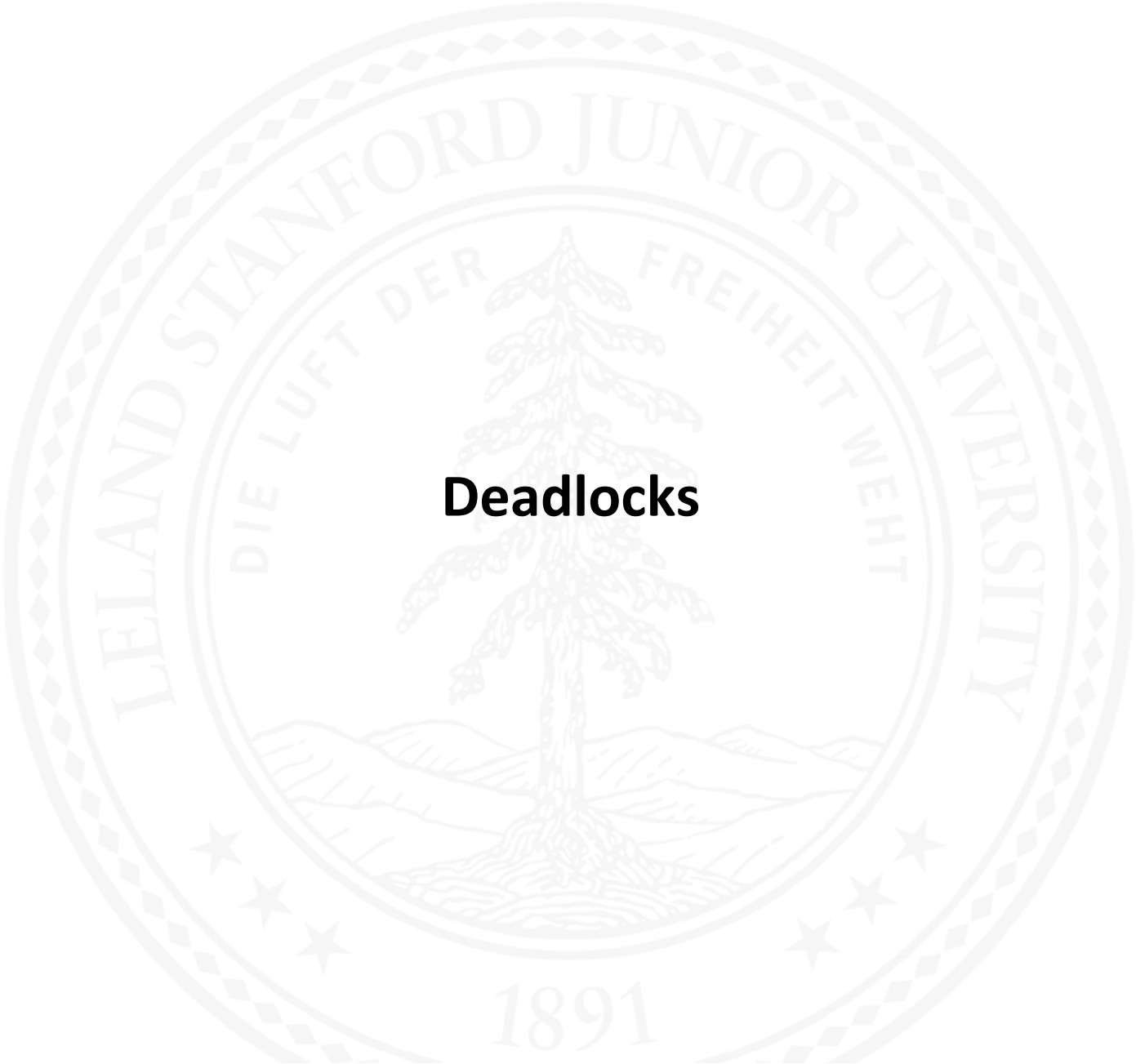
2) Without a buffer



What is the difference?

- Send and Recv are blocking operations:
  - The call does not return until the resources become available again
  - Send: data in buffer can be changed
  - Recv: data in buffer is available and can be used
- Send – If MPI uses a separate system buffer, the data in smessage (user buffer space) is copied (fast); then the main thread resumes.
- If MPI does not use a separate system buffer, the main thread must wait until the communication over the network is complete.
- Recv – If communication happens before the call, the data is stored in an MPI system buffer, and then simply copied into the user provided rmessage when recv() is called.
- The user cannot decide whether a buffer is used or not; the MPI library makes that decision based on the resources available and other factors.


With MPI buffer
send()
Copy to buffer and resume
recv()
Core 0
Core 1
Without MPI buffer
send()
Idle time
recv()
Core 0
Core 1
No buffer is used; the thread needs to wait for the recv()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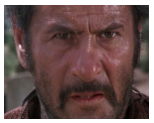
Deadlocks

Deadlocks

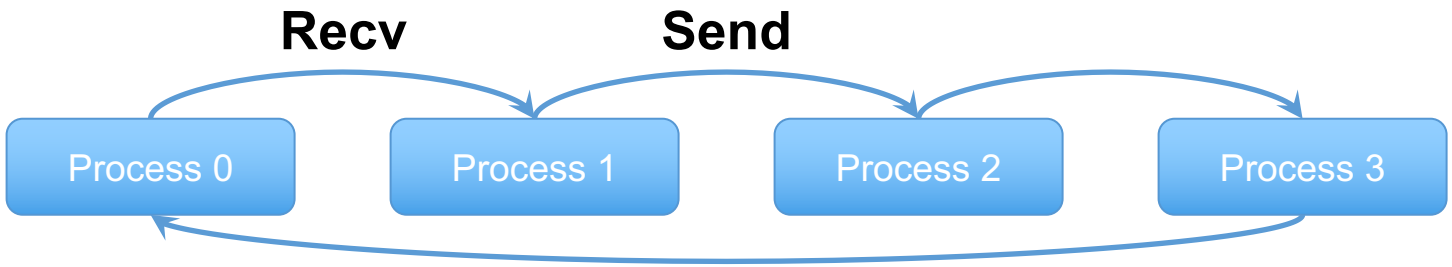
- Because we use blocking routines, deadlocks can occur:

Process 0	Process 1	Deadlock
Recv() Send()	Recv() Send()	Always
Send() Recv()	Send() Recv()	Depends on whether a buffer is used or not
Send() Recv()	Recv() Send()	Secure



- See MPI codes in `mpi_deadlock/` and diagram on next slide.
- **Secure implementation:** code is guaranteed to never deadlock; this should be true independent of whether buffers are used or not.

Ring communication



Code with deadlock

```
// Receive from the lower process and send to the higher process.
int rank_sender = rank==0 ? world_size-1 : rank-1;
MPI_Recv(&number_recv, 1, MPI_INT, rank_sender,
        0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
printf("Process %d received \t %2d from process %d\n", rank,
        number_recv, rank_sender);

int rank_receiver = rank==world_size-1 ? 0 : rank + 1;
MPI_Send(&number_send, 1, MPI_INT, rank_receiver,
        0, MPI_COMM_WORLD);
printf("Process %d sent \t\t %2d to   process %d\n", rank,
        number_send, rank_receiver);
```

“Non-secure” code; can potentially deadlock

```
// Receive from the lower process and send to the higher process.
int rank_receiver = rank==world_size-1 ? 0 : rank + 1;
MPI_Send(&number_send, 1, MPI_INT, rank_receiver,
        0, MPI_COMM_WORLD);
printf("Process %d sent \t\t %2d to   process %d\n", rank,
        number_send, rank_receiver);

int rank_sender = rank==0 ? world_size-1 : rank-1;
MPI_Recv(&number_recv, 1, MPI_INT, rank_sender,
        0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
printf("Process %d received \t %2d from process %d\n", rank,
        number_recv, rank_sender);
```

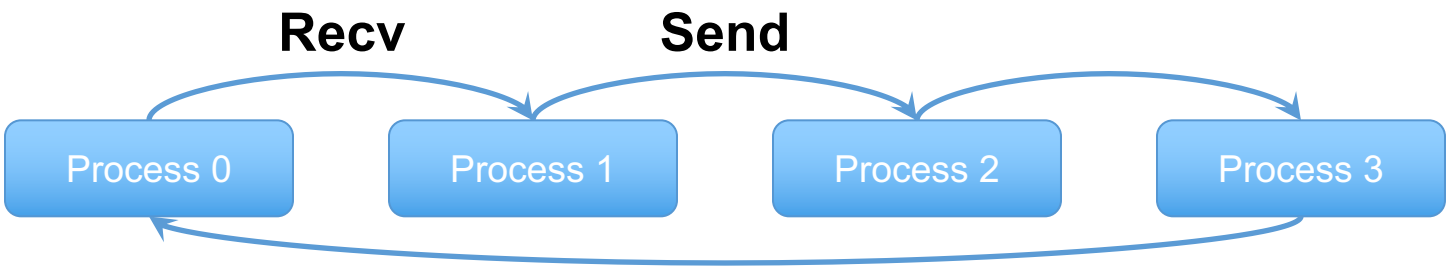
Correct code

```
if(rank % 2 == 0) {
  int rank_receiver = rank==world_size-1 ? 0 : rank + 1;
  MPI_Send(&number_send, 1, MPI_INT, rank_receiver,
           0, MPI_COMM_WORLD);
} else {
  int rank_sender = rank==0 ? world_size-1 : rank-1;
  MPI_Recv(&number_recv, 1, MPI_INT, rank_sender,
           0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
}
if(rank % 2 == 1) {
  int rank_receiver = rank==world_size-1 ? 0 : rank + 1;
  MPI_Send(&number_send, 1, MPI_INT, rank_receiver,
           0, MPI_COMM_WORLD);
} else {
  int rank_sender = rank==0 ? world_size-1 : rank-1;
  MPI_Recv(&number_recv, 1, MPI_INT, rank_sender,
           0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
}
```

Variant using `MPI_Sendrecv`

```
int rank_receiver = rank==world_size-1 ? 0 : rank + 1;
int rank_sender   = rank==0 ? world_size-1 : rank-1;
MPI_Sendrecv(&number_send, 1, MPI_INT, rank_receiver, 0,
             &number_recv, 1, MPI_INT, rank_sender, 0,
             MPI_COMM_WORLD, MPI_STATUS_IGNORE);
```

MPI_Sendrecv




```
MPI_Sendrecv(void *sendbuf, int sendcount,
             MPI_Datatype sendtype,
             int dest, int sendtag,
             void *recvbuf, int recvcount,
             MPI_Datatype recvtype,
             int source, int recvtag,
             MPI_Comm comm, MPI_Status *status)
```

A pair of blocking Send/Recv will synchronize the two processes

True

False

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where every process first send
receives will always deadlock

Yes

No

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ransfer never starts before MPI

True

False

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NON-BLOCKING COMMUNICATIONS

Blocking vs non-blocking

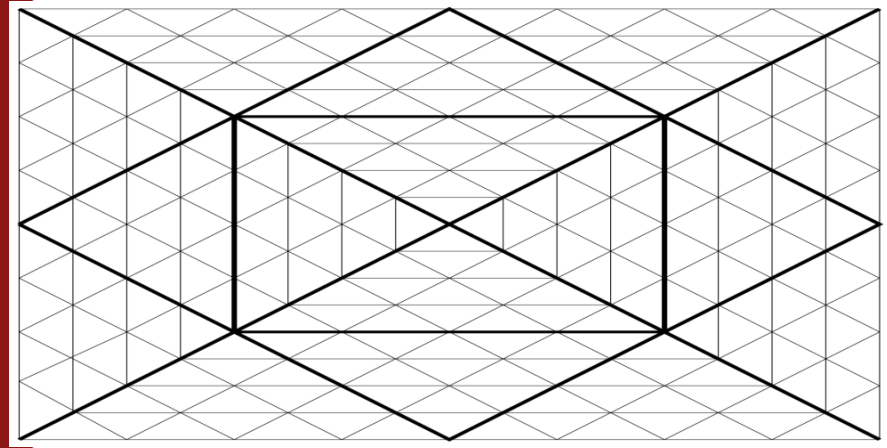
Blocking = you process one communication/task at a time.

Non blocking: communicate while doing something else. Regularly check whether comm has completed.

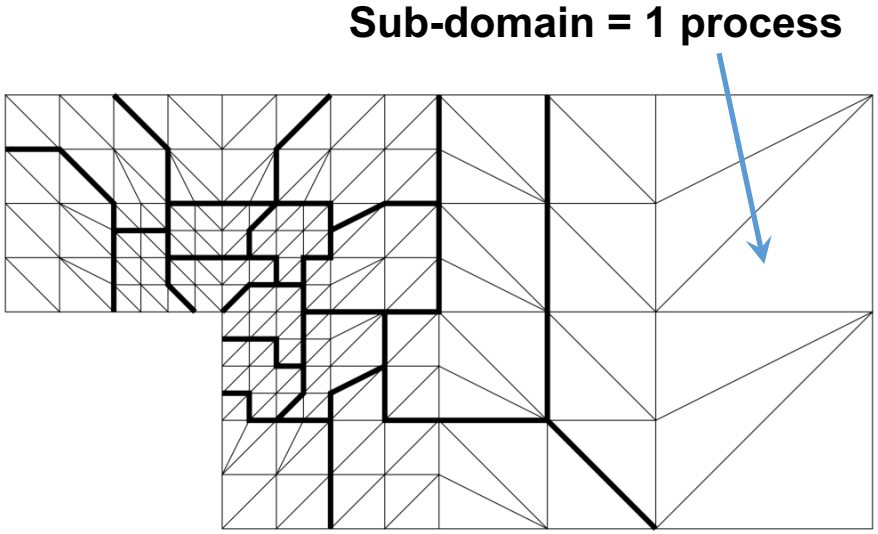
Blocking vs non-blocking

- Blocking communications are convenient:
  - Simple to use.
  - Issue command; once code returns, you know that the task is done (at least the resource is usable).
  - Efficient.
- However, this is too restrictive.
  - When communications are happening, you probably want to do something else, such as do some useful computations or issue other communications. This is called overlapping communications and computations.
  - When you are waiting for several communications to complete, you may be able to do something as soon as one of them completes.
- Non-blocking communications can be used for that purpose:
  - Non-blocking routines return almost immediately.
  - Test routines are used to check the status of the communication.

Finite-element analysis



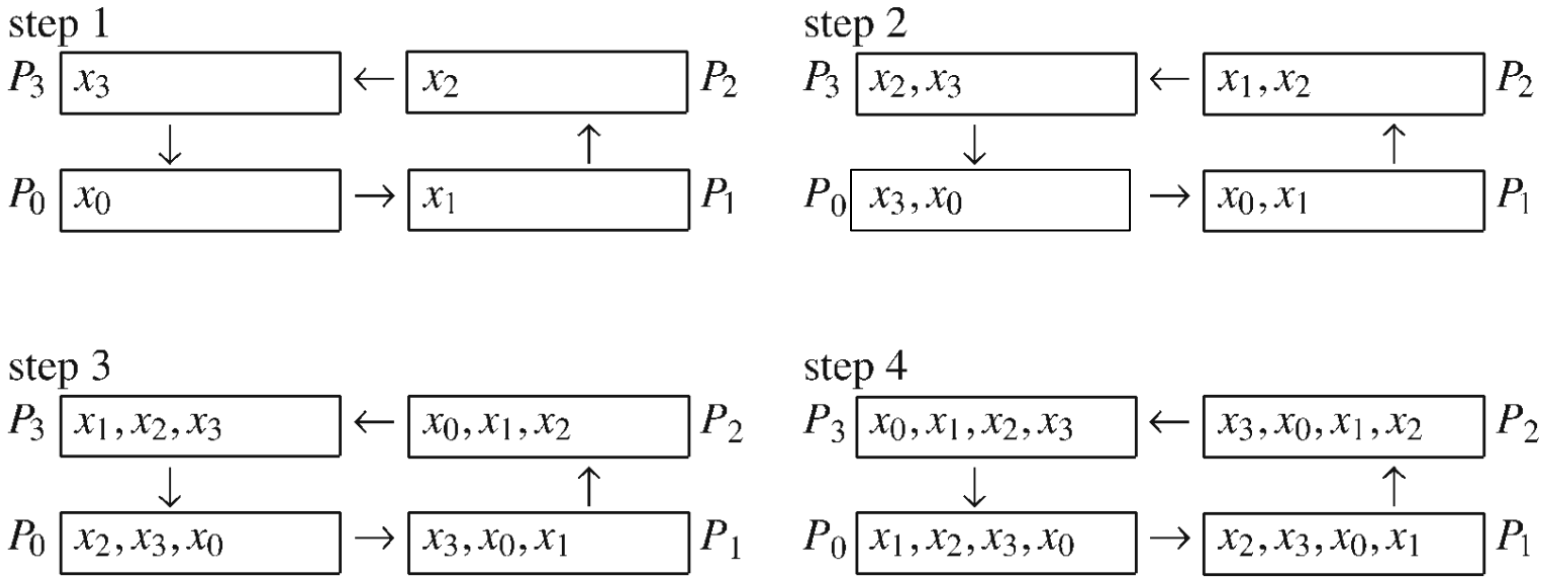
2D rectangular domain



General domain

- MPI communication using Send and Recv. If buffers are used the program will run correctly. Otherwise, deadlocks are possible.
- It's easier to launch all the communications in a non-blocking manner, and then test to check whether they have completed or not.

Gather ring using non-blocking communications



See MPI code: `gather_ring.C`

```
// Vector to store the status of the non-blocking sends
vector<MPI_Request> send_req(nproc-1);
for(int i=0; i<nproc-1; ++i) {
  // Send to the right: Isend
  int* p_send = &numbers[(rank - i + nproc) % nproc];
  MPI_Isend(p_send, 1, MPI_INT, rank_receiver, 0, MPI_COMM_WORLD,
  &send_req[i]); // We can proceed; no need to wait now.
  // Receive from the left: Recv
  int* p_recv = &numbers[(rank - i - 1 + nproc) % nproc];
  MPI_Recv(p_recv, 1, MPI_INT, rank_sender, 0, MPI_COMM_WORLD,
  MPI_STATUS_IGNORE);
  // We need to wait; we cannot move forward until we have that data.
}
```

Non-blocking versions of send and recv

Replace: MPI_send → MPI_Isend

```
int MPI_Isend(void* buf, int count,
       MPI_Datatype datatype,
       int dest, int tag,
       MPI_Comm comm, MPI_Request *request)
```

`MPI_Request*` **use to get information later on about the status of that operation.**

What does I stand for?

Immediate

Testing and waiting

There is a similar non-blocking receive:

```
int MPI_Irecv(void* buf, int count,
        MPI_Datatype datatype,
        int source, int tag,
        MPI_Comm comm, MPI_Request *request)
```

Test the status of the request using:

```
int MPI_Test(MPI_Request *request, int *flag,
    MPI_Status *status)
```

Flag is 1 if request has been completed, 0 otherwise.

Wait until request completes:

```
int MPI_Wait(MPI_Request *request, MPI_Status *status)
```

ossible to deadlock a code with blocking communications?

Yes

No

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Application: bucket and sample sort

- Bucket sort is a simpler parallel algorithm.
- Assume we have a sequence of integers in the interval [a,b].
- Split [a,b] into p sub-intervals.
- Move each element to the appropriate bucket (prefix sum required again).
- Sort each bucket in parallel.
- Simple and efficient!
- A variant of this is the radix sort.
- Problem: how should we split the interval? This process may lead to intervals that are unevenly filled.
- Improved version: sample (or splitter) sort.

Videos of sorting algorithms

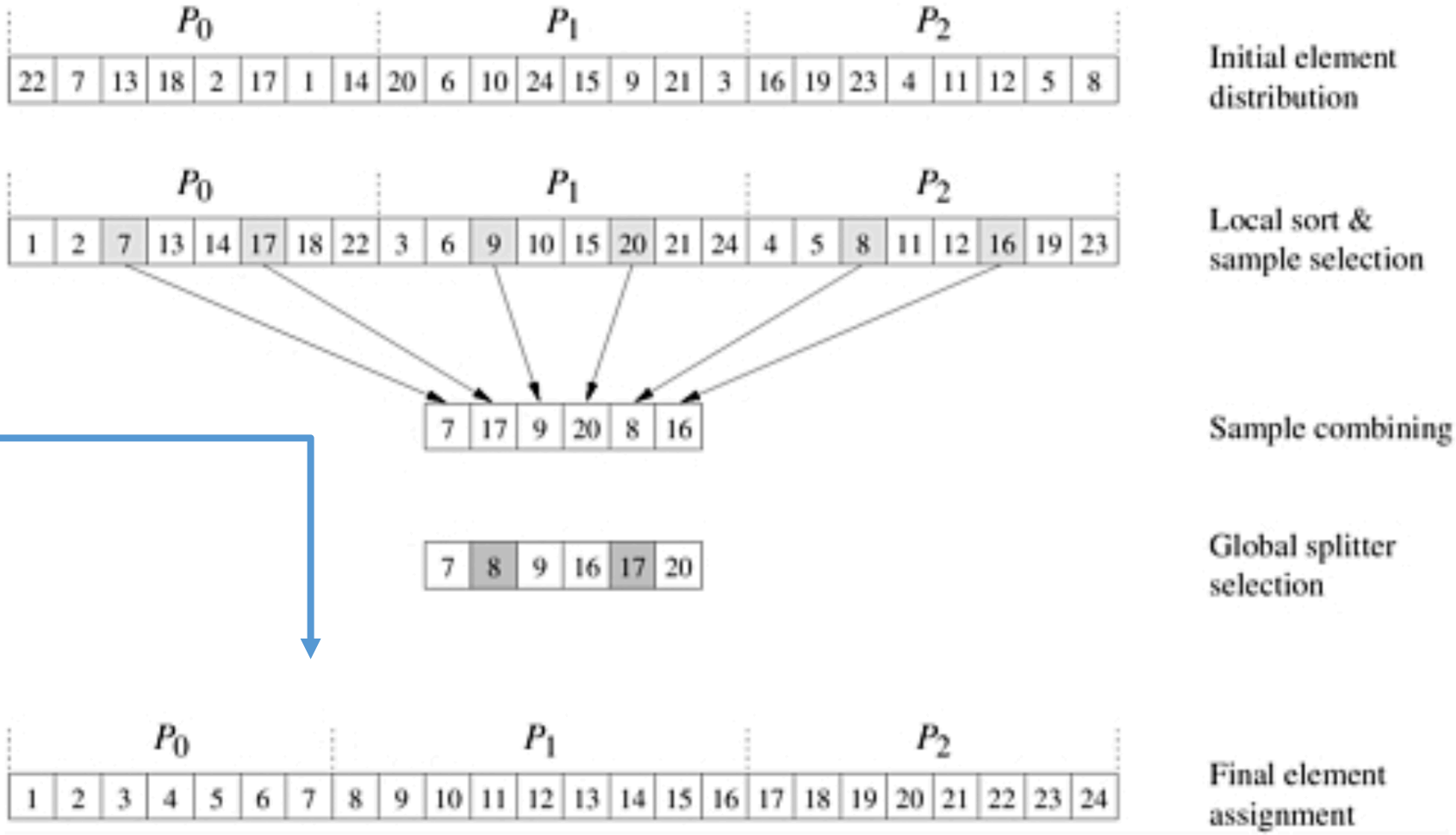
Radix sort

https://www.youtube.com/watch?v=LyRWppObda4

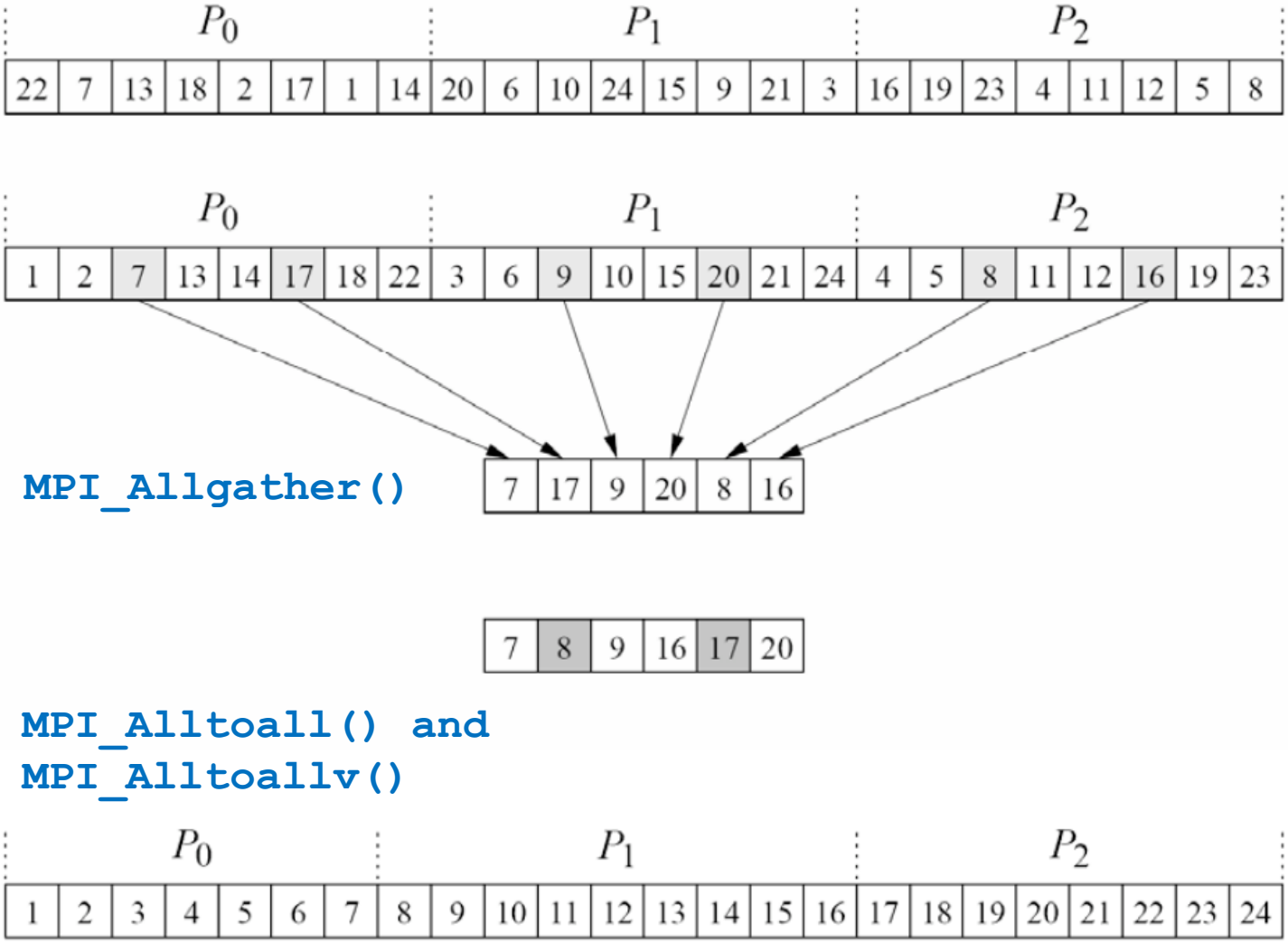
15 sorting algorithms

https://www.youtube.com/watch?v=kPRA0W1kECg

Shared memory: prefix sum required for the final bucket assignment.



Distributed memory



Main challenges

- Load-balancing: the sub-sequences are not always of equal sizes. Depending on the distribution of data, we can get load-imbalances of up to 2x.
- The `AllToAll` communication is a bit complicated because the number of data per process is not the same. Hence, we need `MPI_Alltoallv`.
- This requires an `MPI_Alltoall` to first gather the size of the data to be sent.
- Similarly, the test section at the end requires `MPI_Gatherv`.

Efficiency = Tseq / (n Tpar)

Scalability

```
1 process
   Efficiency: 0.591695; runtime seq: 4.51704, par: 7.63407
2 processes
   Efficiency: 0.587918; runtime seq: 4.47443, par: 3.80532
6 processes
   Efficiency: 0.627524; runtime seq: 4.49705, par: 1.19439
12 processes
   Efficiency: 0.839512; runtime seq: 4.47041, par: 0.443751
24 processes
   Efficiency: 0.789635; runtime seq: 6.97855, par: 0.368237
48 processes
   Efficiency: 0.221131; runtime seq: 6.82009, par: 0.642538
```

The efficiency is excellent, but limited by the fact that we need to sort the vector essentially twice. This explains the slowdown with n=1. Notice that the efficiency increases after that. This is due to a more efficient use of the cache when using multiple cores.