INF560
Algorithmique Parallèle et Distribuée

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Patrick CARRIBAULT

CEA, DAM, DIF, F-91297 Arpajon

Lecture Outline

- Parallel programming
  - Concepts
  - Types
  - Paradigms
  - Message Exchange
- Introduction to MPI
  - Compilation & Execution
  - Main organization
- Point-to-point communications

Parallel Programming

- Concepts

Definition

- Task
  - Work to be done
  - *Very generic name!*

- Thread (or execution flow)
  - Sequence of **sequential** actions resulting from program execution
  - Task implementation

- Process
  - Program instance
  - Composed of one or multiple threads (i.e., multithread process) sharing a common address space

- Parallel computing
  - Consist in splitting a program into multiple tasks that can be executed concurrently to improve global execution time
  - Tasks can be executed (or *scheduled*) by threads inside one or multiple processes
  - Main issue: how to organize those tasks?
    - Notion of *ordering*

Ordering

- Sequential programming
  - Ordered sequence of instructions
  - Sequential semantics
    - As if one instruction can start only if the previous one is retired and its result is available
  - **Total order on instruction execution**

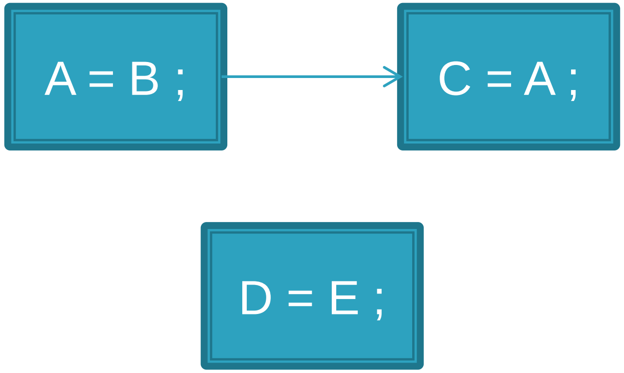
- Parallel programming
  - Several execution flows (instructions and data)
  - Concurrent execution of different instructions
  - Must respect task dependencies
  - **Partial order on instruction execution**

Dependency

- Definition
  - *Task T2 depends on task T1 ➔ T2 requires some results of T1 execution*

- Independent task
  - T2 does not depend on T1

    AND
  - T1 does not depend on T2



- Independent tasks can be executed in any order and/or simultaneously
  - Parallel execution

Parallel Programming

- Types

Parallelism Type

- Need to extract pieces of work (w/ or w/out dependences)

- What are the different *sources* of parallelism?
  - List of non-exhaustive possible approaches

- Three main types:
  - Control parallelism (task-based)
  - Flow parallelism (pipeline)
  - Data parallelism

- Types can be mixed together!

Control Parallelism

- Main idea:
  - *Performing multiple tasks at the same time*

- Where is it available?
  - Applications made of tasks that are independent

- Requirements
  - Need to extract pieces of work (tasks)
    - Choose the right granularity depending on the target execution
  - Need to handle task dependencies
    - Extract the max number of independent tasks (to increase parallelism)
    - Related to graph breadth

Flow Parallelism

- Main idea
  - *Workflow*

- Principle
  - Pipeline approach
  - Input: data stream (one or multiple streams)
  - Application of different tasks on each input data

- Performance
  - Parallelism degree depends on pipeline depth
  - Data input stream should be long and contiguous to avoid pipeline stalls

Data Parallelism

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- Main idea
  - Repeat same actions on similar data
- Principle
  - Data are split into multiple pieces
  - Tasks apply the same work on different subparts
- Performance
  - Parallelism degree is related to the amount of data
  - Correspond to SPMD model (Single Program Multiple Data)

Parallel Programming

- Paradigms

Parallel Programming Paradigm

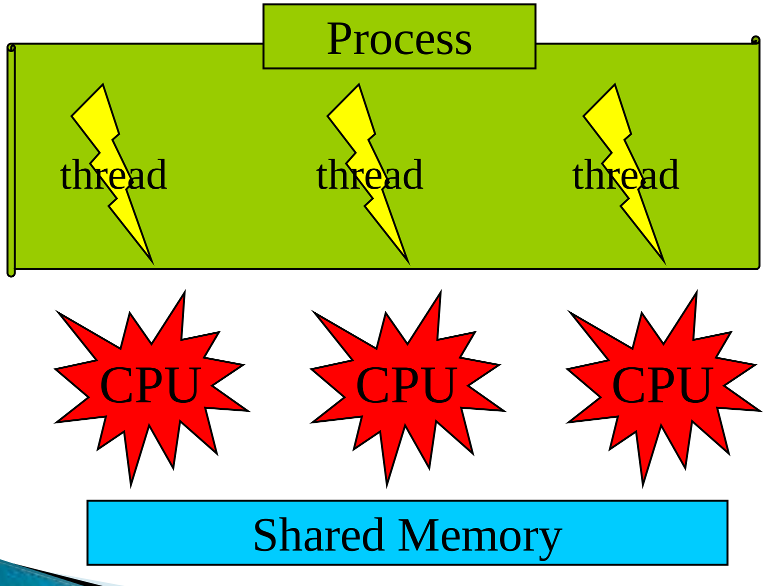
- How to exploit/express the parallelism types?
  - Task
  - Pipeline
  - Data

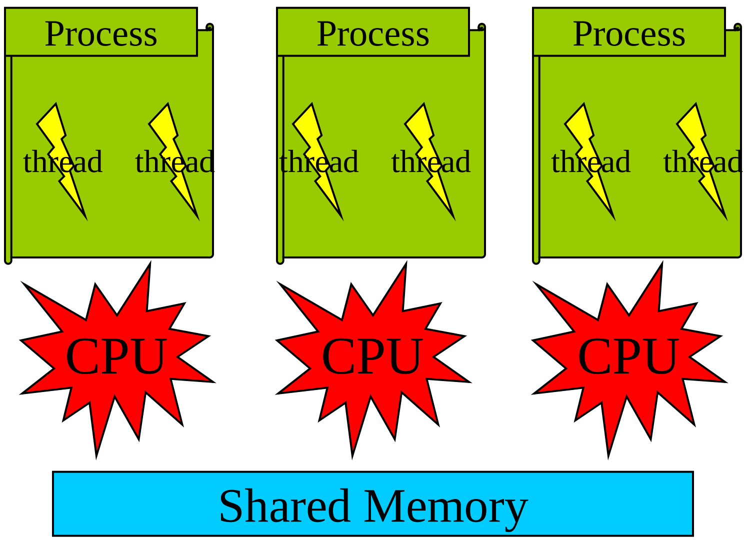
- Need to focus on the system abstraction
  - Based on the main architectures described in Lecture #1
  - System view
    - May not reflect the real hardware implementation

Shared-Memory System

- Shared-memory system
  - System in which multiple compute units share memory
  - Logical or physical

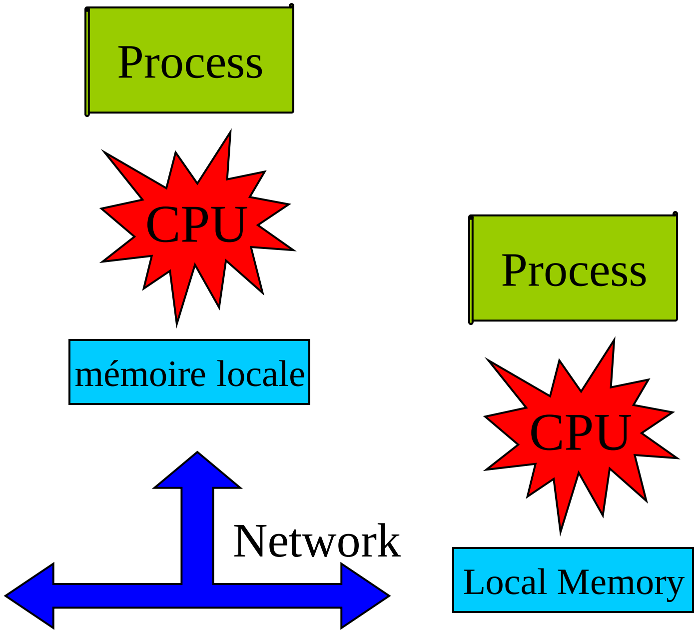
- Node
  - Largest set of units sharing memory





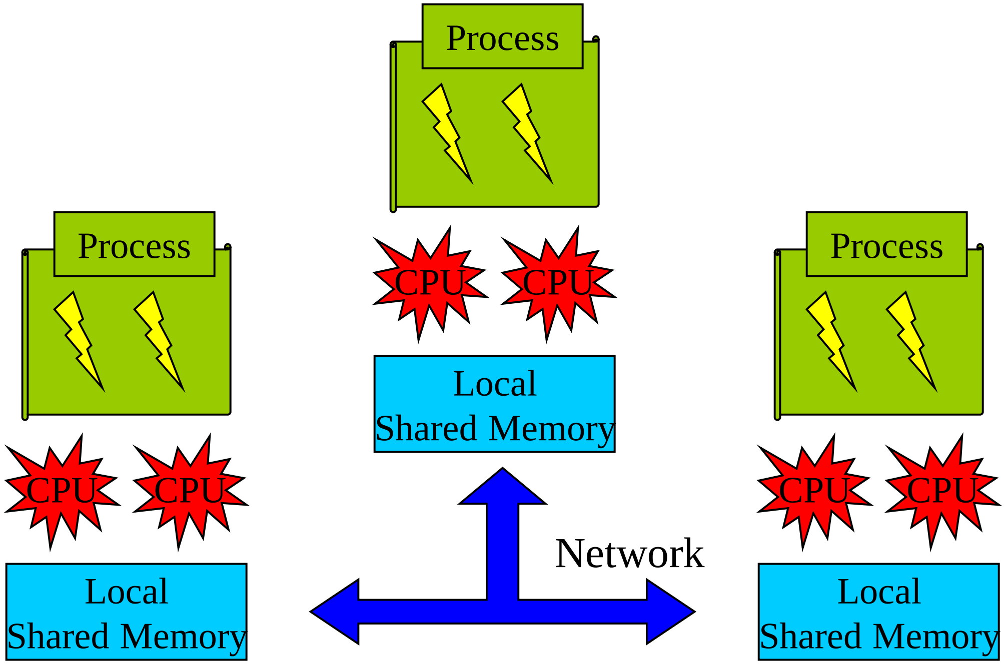
Distributed-Memory System

- Distributed-memory system
  - System in which multiple compute units have their own memory space
  - Units cannot directly access other memories
  - Network may represent inter-socket or inter-core or inter-node connections



Mixed Systems

- Mix of shared and distributed memory systems
- Cluster
  - Set of nodes linked with network



Parallel Programming Paradigm

- Two main paradigms
  - Distributed-memory programming model
  - Shared-memory programming model

- Inspired from system organization

- But: independent from system & hardware
  - In theory, every model can be implemented on any system architecture
  - In practice, mapping of some combinations can be difficult!

Shared-Memory Model

- Requirement
  - **Parallel tasks should have the same view of memory**

- Consequence
  - Concurrent accesses to memory should be handled

- Simple approach but may lead to performance decrease
  - Critical sections/parts are sequential (by definition)
  - Data locality may not be optimal

Shared-Memory Model

- Implementation on distributed-memory system
  - Difficult
  - How to share the memory view?
    - DSM (Distributed Shared Memory)
    - May generate a large overhead
      - Depend on the number of remote accesses
- Implementation on shared-memory system
  - Easy because of shared memory
  - Inside multithreaded process
    - Every thread have access to the same memory zone
    - Usually, whole node memory

Shared-Memory Model: Examples

- POSIX API: pthread
  - Standard thread management inside process
  - Suitable for MPMD approach
  - Mainly C/C++
- OpenMP
  - Compiler directives
  - Hide some management complexity (thread creation, synchronization…)
  - C/C++/FORTRAN
- TBB, Cilk+…
  - Library-based approach
  - Well integrated to C++ (template, objects…)

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Distributed-Memory Model

- Requirements
  - **Parallel tasks work on their own memory space**
  - **Data are split among parallel tasks to enable parallel execution**
- Consequence
  - Need communications between tasks
  - Message-passing programming
- Simple approach for locality
  - Increase data/instruction locality
  - Adapted to SPMD approach

Distributed-Memory Model

- Implementation on distributed-memory system
  - Easy
  - Processes on such systems have to exchange messages which is part of distributed-memory model

- Implementation on shared-memory system
  - Easy as well!
  - Even if tasks may shared memory, the model can hide this feature
  - Implemented with processes, it is possible to use shared-memory segments to improve communication performance

Distributed-Memory Model

- Libraries that expose message passing

- PVM (Parallel Virtual Machine)
  - One of the first library for data exchange
  - Not very used now!

- MPI (Message Passing Interface)
  - Wide-spread standard
  - Outcome of industrial and academic collaboration

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Focus

Parallel Programming

- Message Exchange

Message Exchange

- Message characteristics
  - Sender
  - Destination task
  - Data to exchange

- High-level protocol
  - Pair of actions will resolve message exchange
  - Sender must send the message
    - Let’s consider a function called *send*
  - Recipient must receive the message
    - Let’s consider a function called *recv*

Main Principle

- Two parallel tasks T0 et T1
  - Distinct memory space
  - Each task has its own instructions to execute

T0 Task

instruction1;
instruction2;

T1 Task

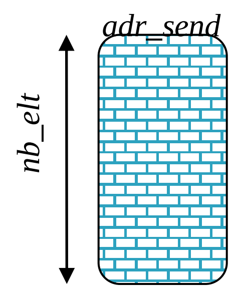
instruction1;
instruction2;

Main Principle

- T1 depends on T0
  - T0 must send data to T1
  - Data are located in *adr_send* with *nb_elt* elements

T0 Task

instruction1;
instruction2;
send(*adr_send*, *nb_elt*, T1);



T1 Task

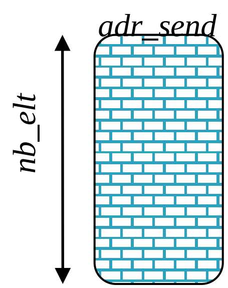
instruction1;
instruction2;

Main Principle

- T1 must receive data from T0 (*recv*)
  - Size of message *nb_elt* should be known by recipient
  - Recipient may have to allocate a memory zone to get the received data (zone pointed by *adr_recv*)

T0 Task

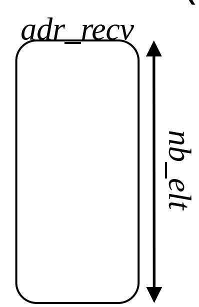
instruction1;
instruction2;
send(*adr_send*, *nb_elt*, T1);



T1 Task

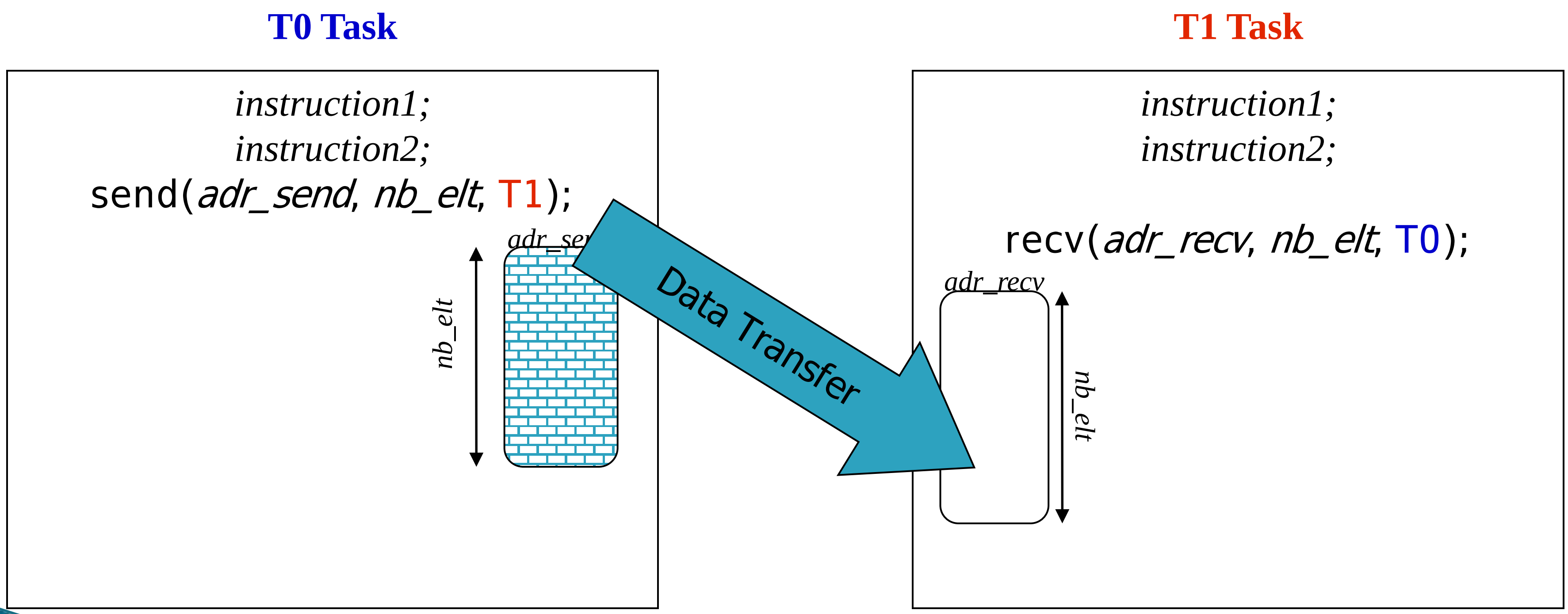
instruction1;
instruction2;

recv(*adr_recv*, *nb_elt*, T0);



Main Principle

- Communication
  - *send* blocks T0 until data are sent
  - *recv* blocks T1 until data are received



Main Principle

- Communication
  - *send* blocks T0 until data are sent
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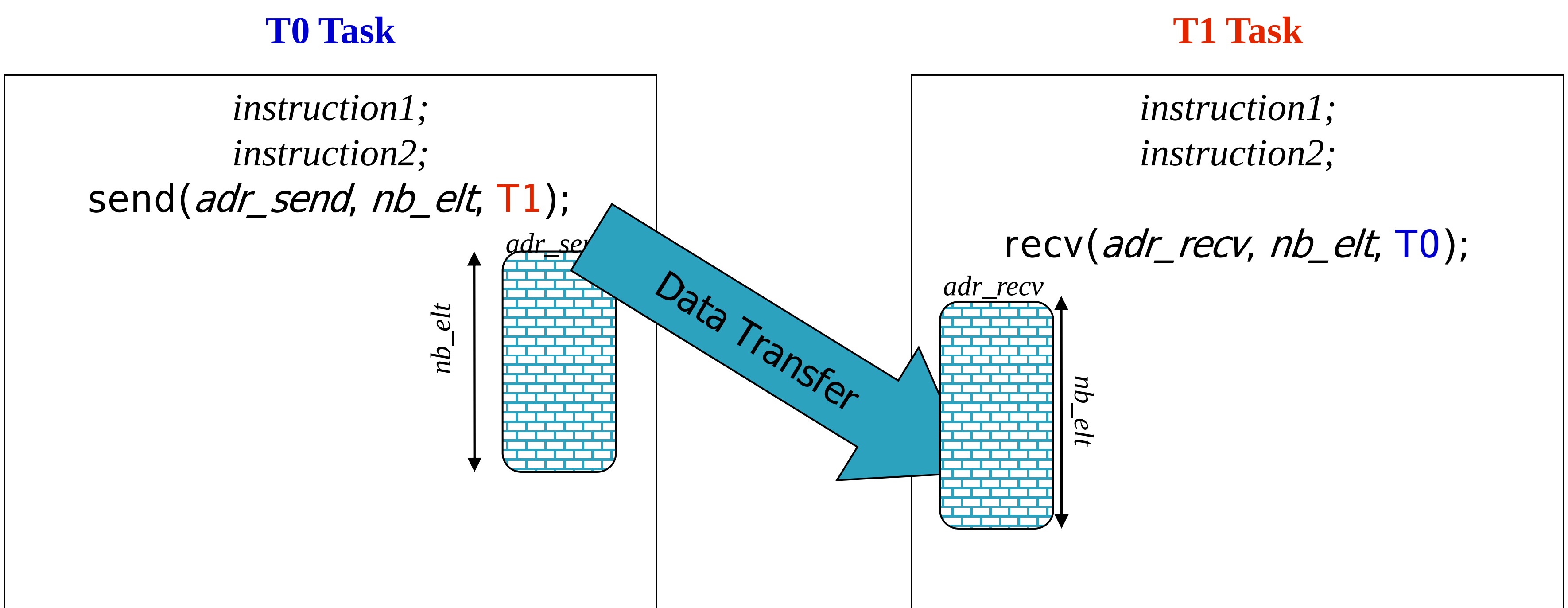
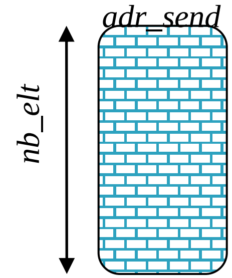


Main Principle

- T1 owns a complete copy of data sent by T0

T0 Task

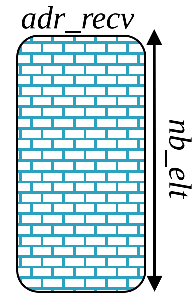
instruction1;
instruction2;
`send(`*adr_send, nb_elt,* `T1);`



T1 Task

instruction1;
instruction2;

`recv(`*adr_recv, nb_elt,* `T0);`



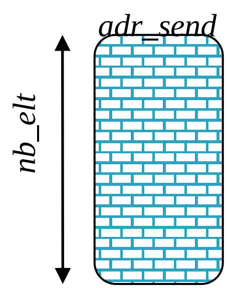
Main Principle

- Tasks T0 and T1 may continue their execution

- Following instructions of T1 may access to data stored at address *adr_recv*

Tâche T0

instruction1;
instruction2;
send(*adr_send*, *nb_elt*, T1);

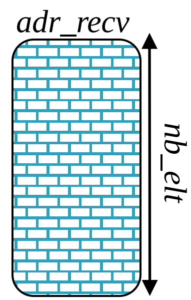


instruction3;

Tâche T1

instruction1;
instruction2;

recv(*adr_recv*, *nb_elt*, T0);



instruction3;

Example

- Parallel sum on each element of an array

- Hypothesis
  - Array t with N floats (N is even)
  - Array t is distributed across 2 tasks T0 and T1
    - Parallelism type: data

- Goal
  - T1 must print the sum of each element of t

- Code?

Example

T0

```
double p = 0.0;
int i;

for( i=0 ; i<N/2 ; i++ )
   p += tab[i];

send( &p, 1, T1);
```

T0 sends its partial sum to T1

T1

```
double p = 0.0;
double s;
int i;

for( i=0 ; i<N/2 ; i++ )
   p += tab[i];

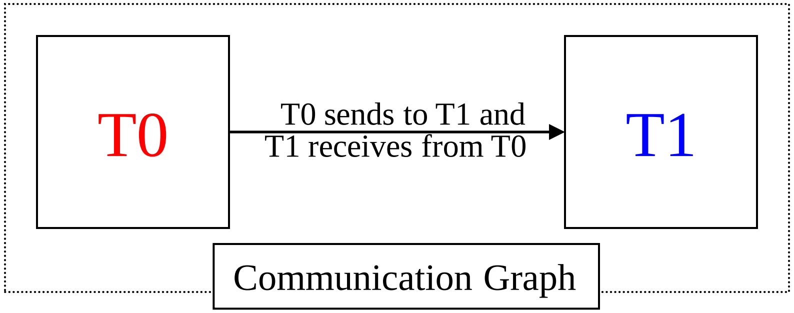
recv(&s, 1, T0);

printf("%g",s+p);
```

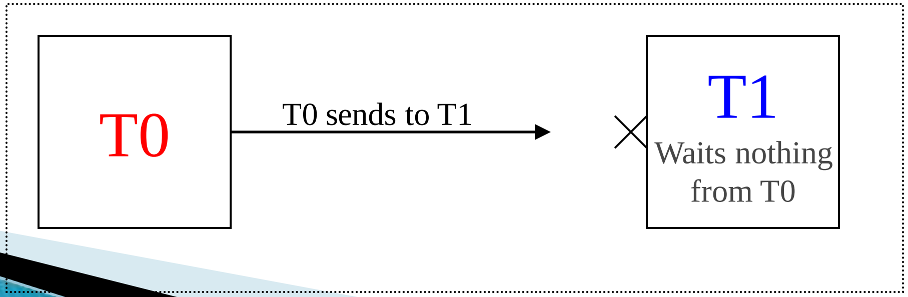
T1 needs partial sum from T0

Send/Recv Matching

- Every *send* corresponds to one *recv* (and vice-versa)
- Model with an oriented graph
  - Vertices are tasks
  - Edges are communications



- A missing send or receive action lead to a deadlock situation



Introduction to MPI

Introduction

- MPI: Message-Passing Interface

- High-level API (Application Programming Interface)
  - Parallel programming
  - Distributed-memory paradigm

- Implementation as a library
  - Interface through functions

- Language compatibility
  - C
  - C++
  - FORTRAN

MPI Overview

- MPI includes (mainly MPI 1)
  - Execution environment
  - Point-to-point communication
  - Collective communications
  - Groups and topologies of tasks
- MPI 2.0 adds
  - One-sided communications
  - Dynamic process creation
  - Multithreading
  - Parallel I/O
- MPI 3.1 adds
  - Non-blocking collectives and I/O
  - RMA
- Lots of features!
  - 120 functions in MPI 1
  - More than 200 for MPI 2

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Hello World!

```
#include <stdio.h>
/* MPI function signatures */
#include <mpi.h>

int main(int argc, char **argv)
{

  /* Initialization of MPI */
  MPI_Init(&argc, &argv);

  printf("Hello World!\n");

  /* Finalization of MPI */
  MPI_Finalize();
  return 0;
}
```

- Header file
  - Need to include it
  - Contains signatures of each available MPI function
  - Function bodies are located inside a library
- Syntax
  - All functions related to MPI start with `MPI_`
- Convention
  - No MPI calls before `MPI_Init`
  - No MPI calls after `MPI_Finalize`

Compilation

- Basically
  - *Compilation process like any other library*

- <u>But</u> multiple ways to compiler an MPI program
  - Simple way: rely on `mpicc` script
  - Complex way: launch regular compiler with options to specify paths to the library

- Simple way
  - Script/program that hide the library configuration details

    ```
    mpicc -o hello hello.c
    ```
  - Call the default underlying compiler
    - Possible to change the compiler that will be invoked
  - <u>This way for the Labs!</u>

Compilation

- Complex way
  - Without the script → pass right options for library
  - configuration
- Generic mandatory options to use external library
  - Directory where header files are located (e.g., `mpi.h`)
  - Directory where library files are located (e.g., `libmpi.so`)
  - Name of the library to use (*linker)*
- Example: `libc` library or MPI library

```
gcc –I/dir/mpi/include –o hello hello.c –L/dir/mpi/lib -lmpi
```

Compiler

Header-file directory

Library directory

Library name

Execution w/ Job Manager

- Slurm can spawn MPI processes
  - Rely on `srun` (if it has been configured) or
  - Rely `salloc` or `sbatch` (w/ mpirun)

- If not available
  - Use of `mpirun` script (different syntax and usage)

```
$ salloc -n 4 mpirun ./hello

Hello World!
Hello World!
Hello World!
Hello World!
```

- Remarks
  - Creation of 4 processes
  - Every process has the same instructions
  - Processes are independent for execution

Execution Through Script

- File
  `hello_1task.batch`

```
#!/bin/bash

#SBATCH -n 1

mpirun ./hello
```

```
$ sbatch hello_1task.batch
Submitted batch job 7168
```

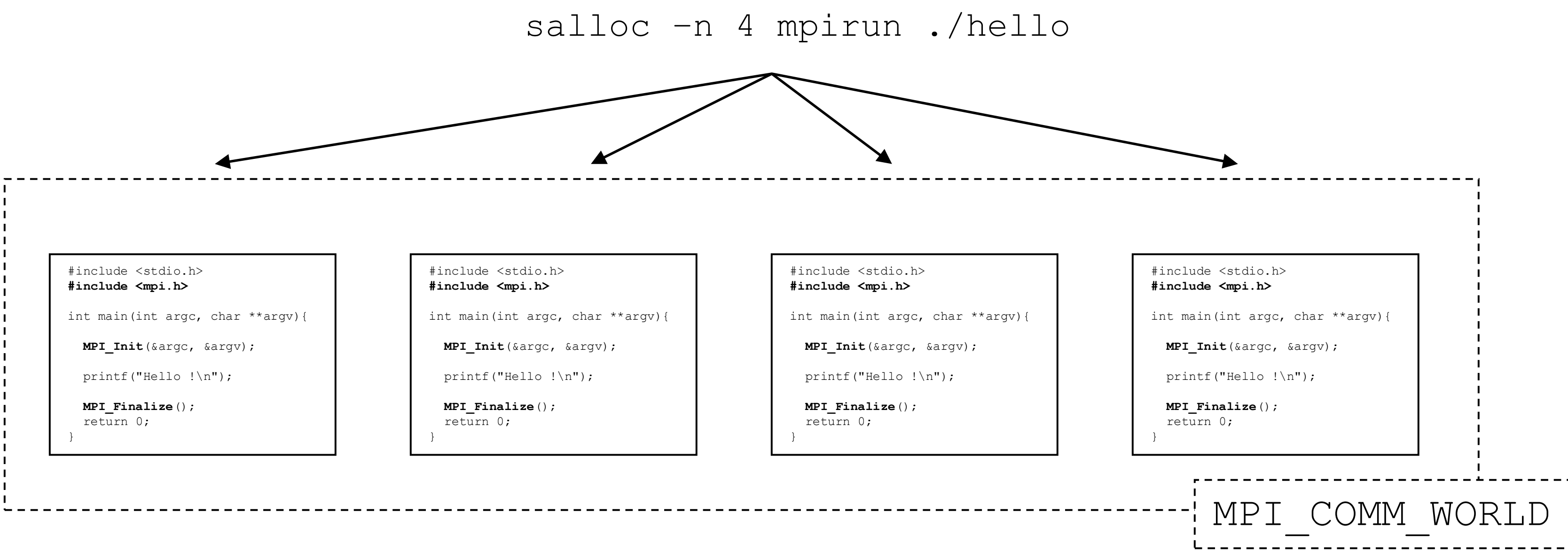
```
$ cat slurm-7168.out
Hello World from task 0 out
of 1 on
allemagne.polytechnique.fr
```

Method for Labs

SLURM Batch Script

Submission

Communicator



- Group of processes form a communicator
  - Predefined: `MPI_COMM_WORLD` w/ all processes
- Communicator = set of processes + communication context
  - Type: `MPI_Comm`

Total Number of Processes

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

int main(int argc, char **argv) {

  int N;
  MPI_Init(&argc, &argv);

  MPI_Comm_size(MPI_COMM_WORLD, &N);

  printf("Number of processes = %d\n", N);

  MPI_Finalize();
  return 0;
}
```

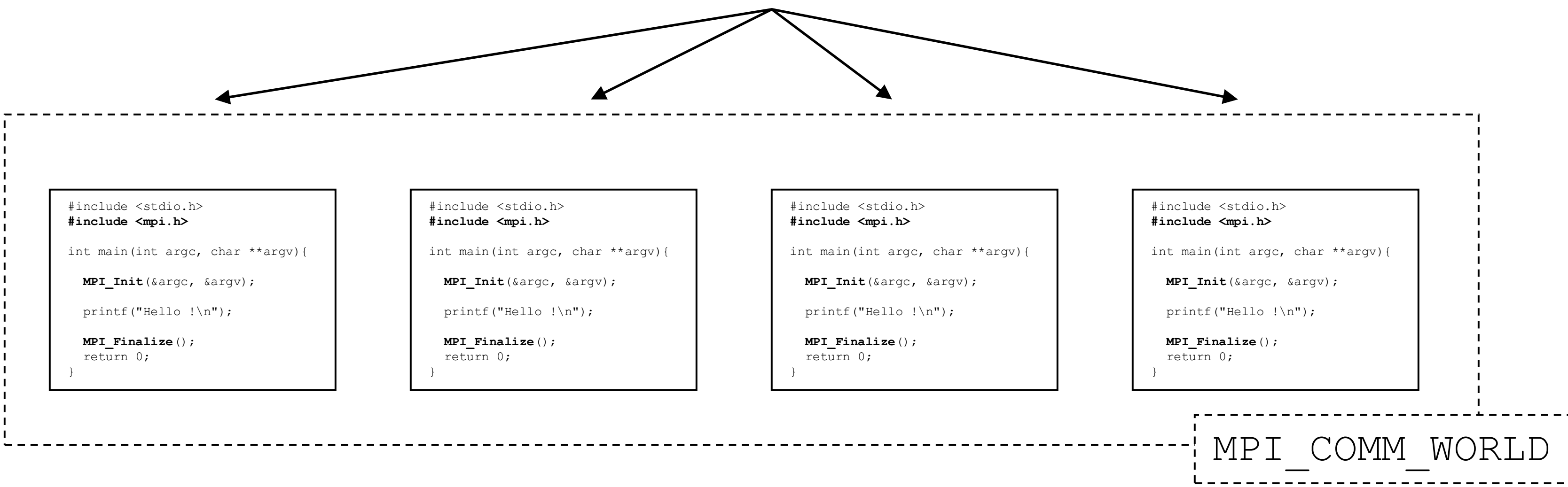
```
% salloc -n 4 mpirun ./a.out
Number of processes = 4
Number of processes = 4
Number of processes = 4
Number of processes = 4
%
```

`int MPI_Comm_size( MPI_Comm comm, int *size);`

- Return size of communicator `comm` in `*size`
- If `comm == MPI_COMM_WORLD`, `MPI_Comm_size` returns the total number of MPI processes in the application

Process Rank

salloc -n 4 mpirun ./hello



- Inside a communicator, MPI assigns rank from 0 to size-1
  - This is the rank of a process
- Function `MPI_Comm_rank` returns the rank in the communicator `comm` inside the address `*rank`:

```
int MPI_Comm_rank(MPI_Comm comm, int *rank);
```

Process Rank

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

int main(int argc, char **argv) {

  int N, me;
  MPI_Init(&argc, &argv);

  MPI_Comm_size(MPI_COMM_WORLD, &N);
  MPI_Comm_rank(MPI_COMM_WORLD, &me);

  printf("My rank is %d out of %d\n", me, N);

  MPI_Finalize();
  return 0;
}
```

```
% salloc -n 4 mpirun ./a.out
My rank is 1 out of 4
My rank is 0 out of 4
My rank is 3 out of 4
My rank is 2 out of 4
%
```

Process Rank

- Number of processes may be different from number of available cores/processors!
  - By default, Slurm binds one MPI process to one core
  - Option `-c` can be used to book multiple cores per rank
- Execution of processes is not related to their rank
  - Parallel execution
  - At the beginning, no ordering between processes
  - Only communications can imply some partial ordering
- Rank is usually used to determine
  - Which part of data should I work on?
  - What is my role (master/slave)?

MPI Point-to-Point Communications

- Send/Recv

MPI Communication

- MPI is a parallel distributed-memory model
  - Each process accesses its own memory space
  - Based on message passing
- What is the main interface for data exchange w/ MPI?
- To send a message
  - `MPI_Send` function

Sending Messages

- Function to send a message

```
int MPI_Send (
      void *buf (in),
      int count(in),
      MPI_Datatype datatype(in),
      int dest(in),
      int tag(in),
      MPI_Comm comm(in)
      );
```

Data address

Data to send inside an array pointed by buf whose elements are of type datatype.

MPI predefined scalar types corresponding to existing C types.

Sending Messages

MPI_Datatype	*C Type*
MPI_CHAR	signed char
MPI_SHORT	signed short int
MPI_INT	signed int
MPI_LONG	signed long int
MPI_UNSIGNED_CHAR	unsigned char
MPI_UNSIGNED_SHORT	unsigned short int
MPI_UNSIGNED	unsigned int
MPI_UNSIGNED_LONG	unsigned long int
MPI_FLOAT	float
MPI_DOUBLE	double
MPI_LONG_DOUBLE	long double
MPI_BYTE	*One byte*
MPI_PACKED	*Pack of non-contiguous data*

Sending Messages

```
int MPI_Send (
      void *buf (in),
      int count(in),
      MPI_Datatype datatype(in),
      int dest(in),
      int tag(in),
      MPI_Comm comm(in)
      );
```

Message size is count.

Not in bytes, but in number of elements of type datatype (portable way to express size).

Sending Messages

```
int MPI_Send (
      void *buf (in),
      int count(in),
      MPI_Datatype datatype(in),
      int dest(in),
      int tag(in),
      MPI_Comm comm(in)
      );
```

Communicator for message.

Communicator = (sub-)set of processes + communication context

MPI_COMM_WORLD contains all processes created during application launch

Sending Messages

```
int MPI_Send (
      void *buf (in),
      int count(in),
      MPI_Datatype datatype(in),
      int dest(in),
      int tag(in),
      MPI_Comm comm(in)
      );
```

Recipient rank.

This rank is valid inside communicator comm.

For MPI_COMM_WORLD, dest should be between 0 and number of tasks (excl.).

Sending Messages

```
int MPI_Send (
      void *buf (in),
      int count(in),
      MPI_Datatype datatype(in),
      int dest(in),
      int tag(in),
      MPI_Comm comm(in)
      );
```

Label named tag used to identify messages.

Allows distinguish messages from the same sender and the same recipient.

Summary on Sending Messages

- `MPI_Send` is blocking function
  - Returning from `MPI_Send` , process can manipulate (e.g., write) the data buffer containing the message
  - It doesn't mean that
    - Message has been sent
    - Message has been received

- How to determine the message tag
  - Can use any way you want
  - Not necessary for different send/recipient pair
  - Example:

```
tag = src * N + dest
```

  `N` total number of MPI processes,
  `src` sender rank,
  `dest` recipient rank;

- Be careful: the number of tags is limited!

MPI Communication

- What is the main interface for data exchange w/ MPI?

- Message reception
  - `MPI_Recv` function

Receiving Messages

```
int MPI_Recv (
    void *buf(out),
    int count(in),
    MPI_Datatype datatype(in),
    int source(in),
    int tag(in),
    MPI_Comm comm(in),
    MPI_Status *status(out)
    );
```

Main characteristics of message to receive

Receiving Messages

```
int MPI_Recv (
      void *buf(out),
      int count(in),
      MPI_Datatype datatype(in),
      int source(in),
      int tag(in),
      MPI_Comm comm(in),
      MPI_Status *status(out)
      );
```

Address of memory zone to put the received data.

This zone should be allocated in some way BEFORE!

Max size of received message

Unit is in number of elements of type datatype.

The actual size of received message is less or equal to count.

Receiving Messages

```
int MPI_Recv (
    void *buf(out),
    int count(in),
    MPI_Datatype datatype(in),
    int source(in),
    int tag(in),
    MPI_Comm comm(in),
    MPI_Status *status(out)
);
```

Rank of sender.

Rank should be valid in comm communicator.

Can specify the predefined value `MPI_ANY_SOURCE` → May match a message from any sender in the target communicator

Message tag.

Should be the same of the one put in corresponding `MPI_Send` function call.

Receiving Messages

```
int MPI_Recv (
      void *buf(out),
      int count(in),
      MPI_Datatype datatype(in),
      int source(in),
      int tag(in),
      MPI_Comm comm(in),
      MPI_Status *status(out)
      );
```

Information about received message

Information and Status

- `MPI_Status` is a C structure

```
struct MPI_Status {
    int MPI_SOURCE; /* message sender (useful w/ MPI_ANY_SOURCE argument) */
    int MPI_TAG; /* message tag (useful w/ MPI_ANY_TAG argument) */
    int MPI_ERROR; /* error code */
};
```

- If message size is unknown to the recipient, it is possible to extract the actual size with `MPI_Get_count`

```
int MPI_Get_count(
    MPI_Status *status(in), /* status returned by MPI_Recv */
    MPI_Datatype datatype(in), /* Type of elements in the message */
    int *count(out) /* Size of the message (in number of elements
                                    of type datatype) */
    );
```

Simple MPI Example (2 Tasks)

```
int main(int argc, char **argv) {
  double sum = 0.0, s;
  int i, r;
  MPI_Status status;

  MPI_Init(&argc, &argv); /* Initialization of MPI library */
  MPI_Comm_rank(MPI_COMM_WORLD, &r); /* Get the rank of current task */

  for( i = 0 ; i < N/2 ; i++ )
    sum += tab[i]; /* Each process has half of the global array */

  tag = 1000; /* Message tag */
  if (r == 0) {
    MPI_Send(&sum, 1, MPI_DOUBLE, 1, tag, MPI_COMM_WORLD);
  } else {
    MPI_Recv(&s, 1, MPI_DOUBLE, 0, tag, MPI_COMM_WORLD, &status);
    printf( "Sum = %d\n", s+sum );
  }
  MPI_Finalize();
  return 0;
}
```

Valid for 2 tasks.
What about P tasks?

Simple MPI Example (P Tasks)

```
sum = 0.;                        /* Each process has N/P elements of distributed */
for( i = 0 ; i < N/P ; i++ )     /* array and perform a partial sum              */
  sum += tab[i];

if (r == 0) {
  /* Process 0 receives P-1 messages in any order */
  for( t = 1 ; t < P ; t++ ) {

    MPI_Recv(&s, 1, MPI_DOUBLE,
             MPI_ANY_SOURCE, MPI_ANY_TAG, /* wildcards */
             MPI_COMM_WORLD, &sta);

    printf( "Message from rank %d\n", sta.MPI_SOURCE);

    sum += s; /* Contribution of process sta.MPI_SOURCE to the global sum */
  }

} else {

  /* Other processes send their partial sum to rank 0 */
  MPI_Send(&sum, 1, MPI_DOUBLE, 0, rang, MPI_COMM_WORLD);
}
```

Blocking Communications

- `MPI_Send` et `MPI_Recv` are blocking
  - `MPI_Send` returns when data buffer can be manipulate again by sender
  - `MPI_Recv` returns when the message arrived and has been processed

- Issue?
  - Be careful to deadlock situations!

Ring Topology

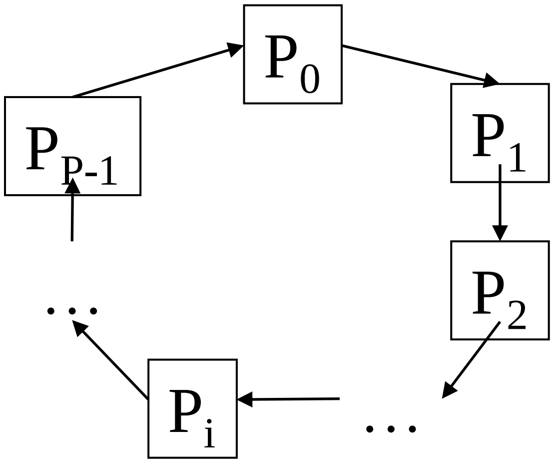
```
left = (rank + P - 1) % P;
right = (rank + 1) % P;

if (rank == 0)
   m = 0;

/* Receiving from left-hand side */
MPI_Recv(&m, 1, MPI_INT, left, tag1, MPI_COMM_WORLD, &sta);

/* Sending to right-hand side */
MPI_Send(&m, 1, MPI_INT, right, tag2, MPI_COMM_WORLD);
```

<u>Ring example:</u>
Processes pass one message in increasing rank value



Ring Topology

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left = (rank + P - 1) % P;
right = (rank + 1) % P;

if (rank == 0)
   m = 0;

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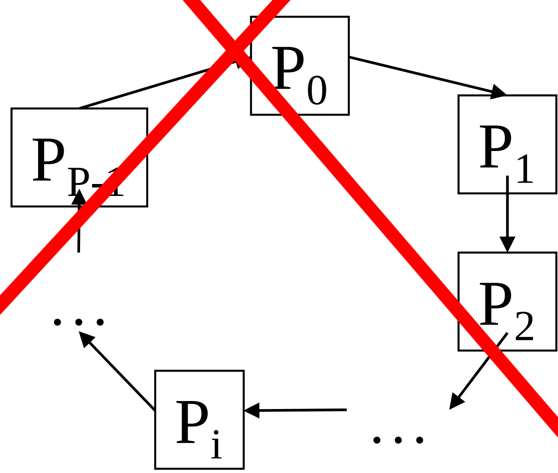
```

<u>Ring example:</u>
Processes pass one message in increasing rank value



Each process P_i waits a message from P_{i-1} before sending it to P_{i+1}. To do so, P_{i-1} should send this message, but P_{i-1} is blocked because it wait for a message from P_{i-2}…

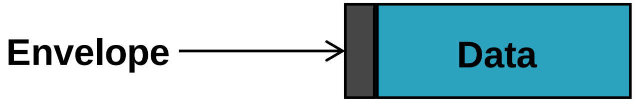
$\Rightarrow$ **deadlock**

MPI Point-to-Point Communications

- Protocols

Message Protocols

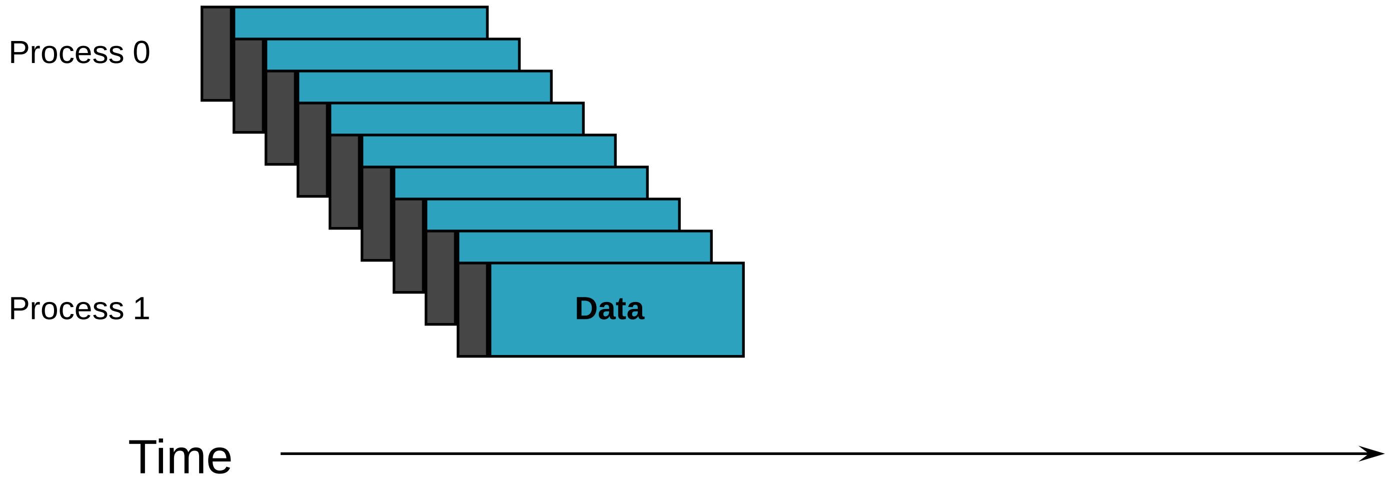
- Message consists of “envelope” and data
  - Envelope contains tag, communicator, length, source information, plus impl. private data



- Multiple possible protocols
  - Eager
    - Message sent assuming destination can store
  - Rendezvous
    - Message not sent until destination oks

Eager Protocol

- Data delivered to process 1
  - No matching receive may exist; process 1 must then buffer and copy.



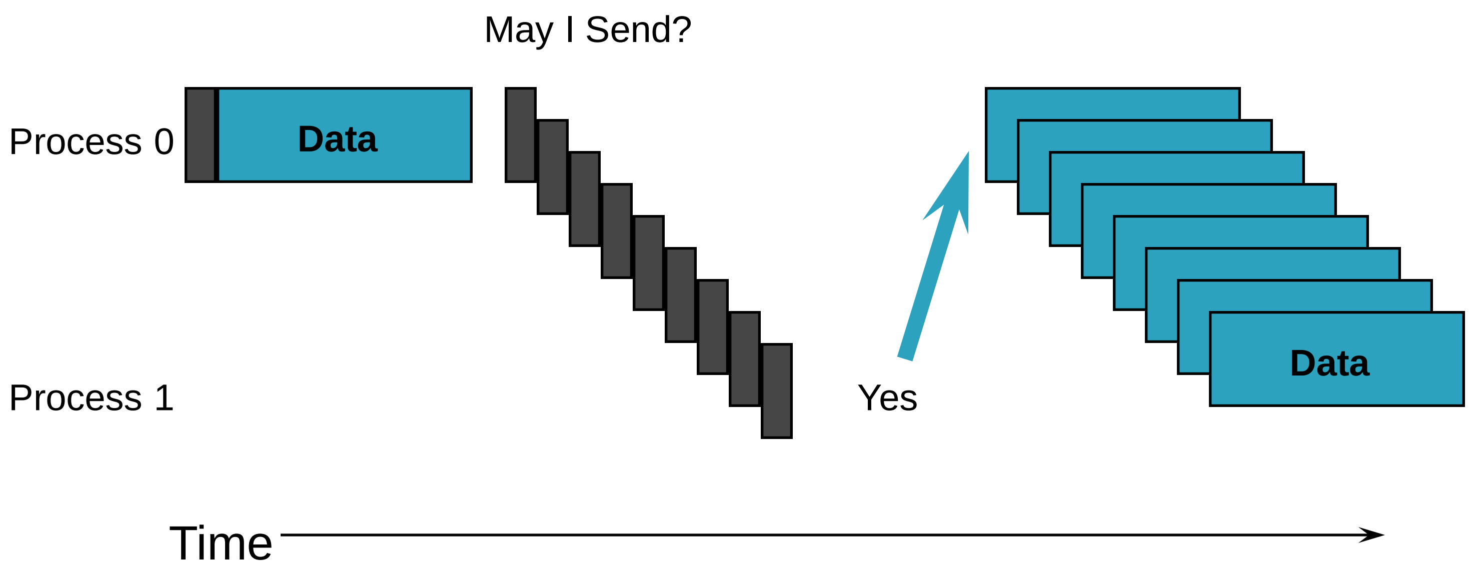
Eager Features

- Reduces synchronization delays
- Simplifies programming (just `MPI_Send`)
- Requires significant buffering
- May require active involvement of CPU to drain network at receiver's end
- May introduce additional copy (buffer to final destination)

How Scalable is Eager Delivery?

- Buffering must be reserved for arbitrary senders
- User-model mismatch (often expect buffering allocated entirely to “used” connections).
- Common approach in implementations is to provide same buffering for all members of MPI_COMM_WORLD; this is optimizing for non-scalable computations
- Scalable implementations that exploit message patterns are possible

Rendezvous Protocol



- Envelope delivered first
- Data delivered when user-buffer available
  - Only buffering of envelopes required

Rendezvous Features

- Robust and safe
  - (except for limit on the number of envelopes…)
- May remove copy (user to user direct)
- More complex programming (waits/tests)
- May introduce synchronization delays (waiting for receiver to ok send)

MPI Point-to-Point Communications

- Blocking Communications

Blocking Communications

- Definition
  - A *send* is **blocking** if after performing *send* it is possible to manipulate (read/write) the input data buffer without corrupting the communication

- Meaning
  - A blocking *send* will not return while the communication library is not able to handle the message

Blocking Communications

T0

```
a = 100;
send(&a, 1, T1);
a = 0;
```

T1

```
recv(&a, 1, T0);
printf("%d\n", a);
```

- After *send*, T0 may modify the value of `a`
- T1 will receive 100 (value of `a` as input of *send* by T0)

- Note
  - Resolving a blocking send does not mean that the receiver has the message

Blocking Communications

- Definition
  - A *recv* is **blocking** if after performing *recv* the output buffer contains the received message

- Meaning
  - A blocking *recv* will not while the message has not been received and processed

Blocking Communications

T0

```
a = 100;
send(&a, 1, T1);
a = 0;
```

T1

```
recv(&a, 1, T0);
printf("%d\n", a);
```

- After *send*,
  - T0 may manipulate `a` and its content
- After *recv*,
  - Content of output buffer (`a` in T1) can be manipulated (read, write, print…) without concurrency issue

Communication Mode

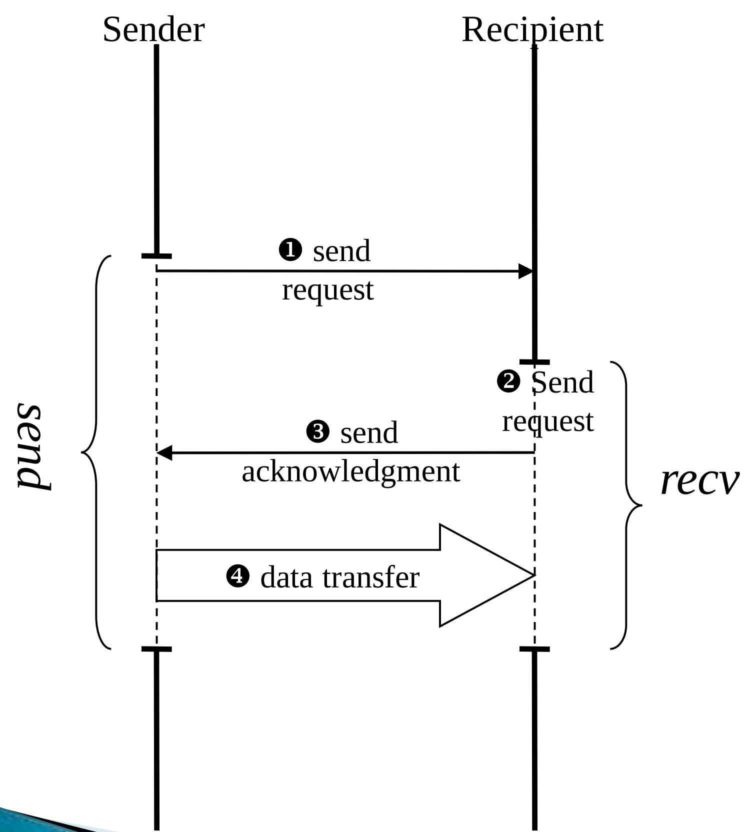
- Multiple modes for blocking communications
  1. **Synchronous mode**
  2. Buffered mode
  3. Standard mode

Synchronous Mode

- Definition
  - A **synchronous send** will block while the message has not been received by the recipient
- Implementation
  - Require some sort of synchronization mechanism between sender and recipient
  - Design of a data-transfer protocol

Synchronous Mode

- Synchronous communication protocol



❶ For a synchronous send, sender transfer a request to the receiver and waits for an answer

❷ When recipient starts the `recv` function, it waits for a sender request

❸ When recipient has the expected request, it answers with an acknowledgment message

❹ Sender and recipient are now synchronized leading to a safe data transfer

Synchronous Mode

- Advantages
  - No intermediate copy inside internal buffer
  - May rely on optimized direct remote memory access (DMA or RDMA)
- Drawbacks
  - Involve a remote synchronization (*rendez-vous*) between the two tasks
  - May lead to idle overhead
- Optimal situation
  - When sender and recipient calls the corresponding function *at the same time*
  - Possible in data parallelism when load is balanced between the two tasks

MPI Synchronous Mode

```
int MPI_Ssend (
   void *buf (in),
   int count(in),
   MPI_Datatype datatype(in),
   int dest(in),
   int tag(in),
   MPI_Comm comm(in)
);
```

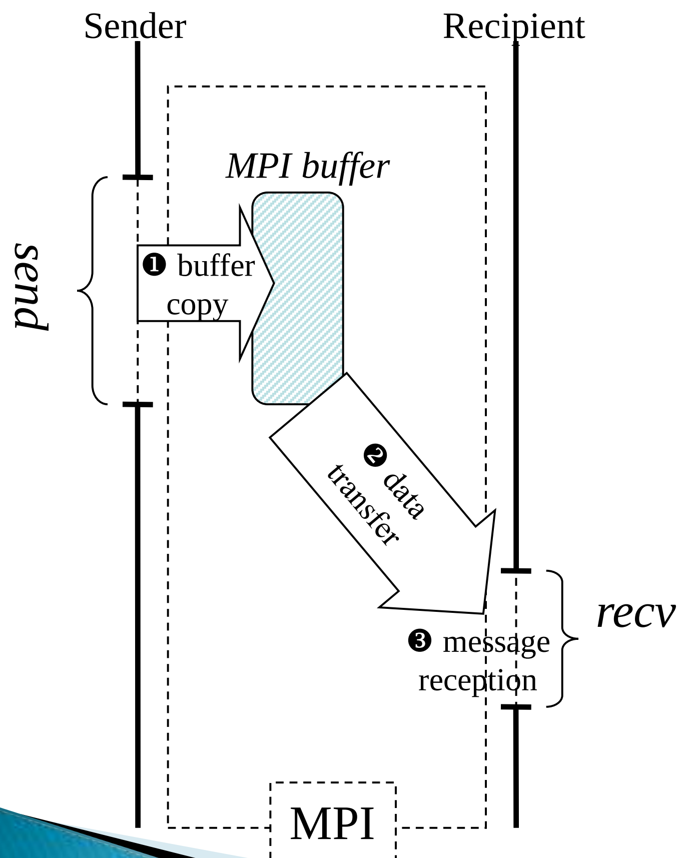
- Same signature as `MPI_Send`.
- Message received through `MPI_Recv`

Communication Mode

- Multiple modes for blocking communications
  1. Synchronous mode
  2. **Buffered mode**
  3. Standard mode

Buffered Mode

- Waits until message has been copied to internal buffer
- Protocol:



❶ Sender copies incoming message inside a buffer (managed by the communication library). Send function may return

❷ Communication library owns a copy of the data to transfer and sends it to the recipient

❸ Recipient gets the message asap

Buffered Mode

- Advantages
  - Ability to decouple *send* and *recv* actions: *send* may return before recipient calls *recv* function
- Drawbacks
  - Intermediate data copy
    - CPU overhead
    - Memory consumption overhead
    - Memory bandwidth overhead
  - Limited to an upper bound (buffer size)
- Optimal situations
  - When *send* and *recv* functions are not posted *at the same time*
  - Load is not balanced between tasks

Buffer Allocation

- User may provide its own buffer to replace the internal one.
  - Function to attach user-allocated buffer `buf` of size `sz` bytes

```
int MPI_Buffer_attach(void *buf, int sz);
```

- Such buffer can be released and used again in the application by the user
  - Function to detach a user-allocated buffer
  - Return the buffer start address and its size

```
int MPI_Buffer_detach(void **buf_adr, int *sz);
```

Buffer Allocation

```
#define BUFFSIZE 100000
int sz;
char *buf;

MPI_Buffer_attach( malloc(BUFFSIZE), BUFFSIZE );
…
MPI_Bsend(msg1, …);
MPI_Bsend(msg2, …);
…
MPI_Buffer_detach( &buf, &sz );
free(buf);
```

- Only used in `MPI_Bsend`
- Only one buffer may be attached
- Only useful for sender

Communication Mode

- Multiple modes for blocking communications
  1. Synchronous mode
  2. Buffered mode
  3. **Standard mode**

Standard Mode

- Function for standard communication
  - `MPI_Send`

- Standard communication protocol
  - MPI includes an internal threshold T
    - If input message size is lower than T
      - Switch to buffered mode
    - If input message size is larger than T
      - Switch to synchronous mode

Standard Mode

```
if ( rang == 0 )
        n = 1;
else if ( rang == 1 )
        n = 0;

MPI_Send(&msg1, N, MPI_BYTE, n, tag1, comm);
MPI_Recv(&msg2, N, MPI_BYTE, n, tag2, comm);
```

- Is this code safe?
- NO
  - If N is small enough → OK
  - If N is too large → Deadlock

Standard Mode

- Hint to detect such issues
  - Replace calls to `MPI_Send` by `MPI_Ssend`
  - Whatever the size of messages and scheduling, the applications should not deadlock

- Deadlocks mean application bugs!

MPI Point-to-Point Communications

- Non-Blocking Communications

Non-Blocking Communication

- Definition
  - A **non-blocking** communication has not guarantee when function returns!
- Meaning
  - No safe access to input message when function send returns
  - To be sure that message buffer can be reused, an additional function should be called and returned

Non-Blocking Send `MPI_Isend`

```
int MPI_Isend (
   void *buf (in),
   int count(in),
   MPI_Datatype datatype(in),
   int dest(in),
   int tag(in),
   MPI_Comm comm(in),
   MPI_Request *req(out)
);
```

One additional argument MPI_Request *req.

Request id is returned in *req (MPI_Request = MPI opaque type).

Check Function `MPI_Wait`

```
int MPI_Wait (
        MPI_Request *req(inout),
        MPI_Status *sta(out)
);
```

`MPI_Wait` blocks until communication represented by `*req` is done.

Detailed information about completed communication are store into `*sta`.

When `MPI_Wait` returns

- `*req` is assigned to `MPI_REQUEST_NULL` (invalid request)
- Input message buffer can be safely manipulated by sender

Remark:

`MPI_Send` ⇔ `MPI_Isend` + `MPI_Wait`

Non-Blocking Example

```
MPI_Request req;
MPI_Status sta;

MPI_Isend(buf, N, MPI_BYTE,
dest, tag1, comm,
&req);

instruction1;
instruction2;
…
instructionN;

MPI_Wait(&req, &sta);
```

Instructions between `MPI_Isend` and `MPI_Wait` should not write into `buf`.

In the meantime, message *can/may* progress

- Advantages
  - Recover communications and computation

Non-Blocking Reception

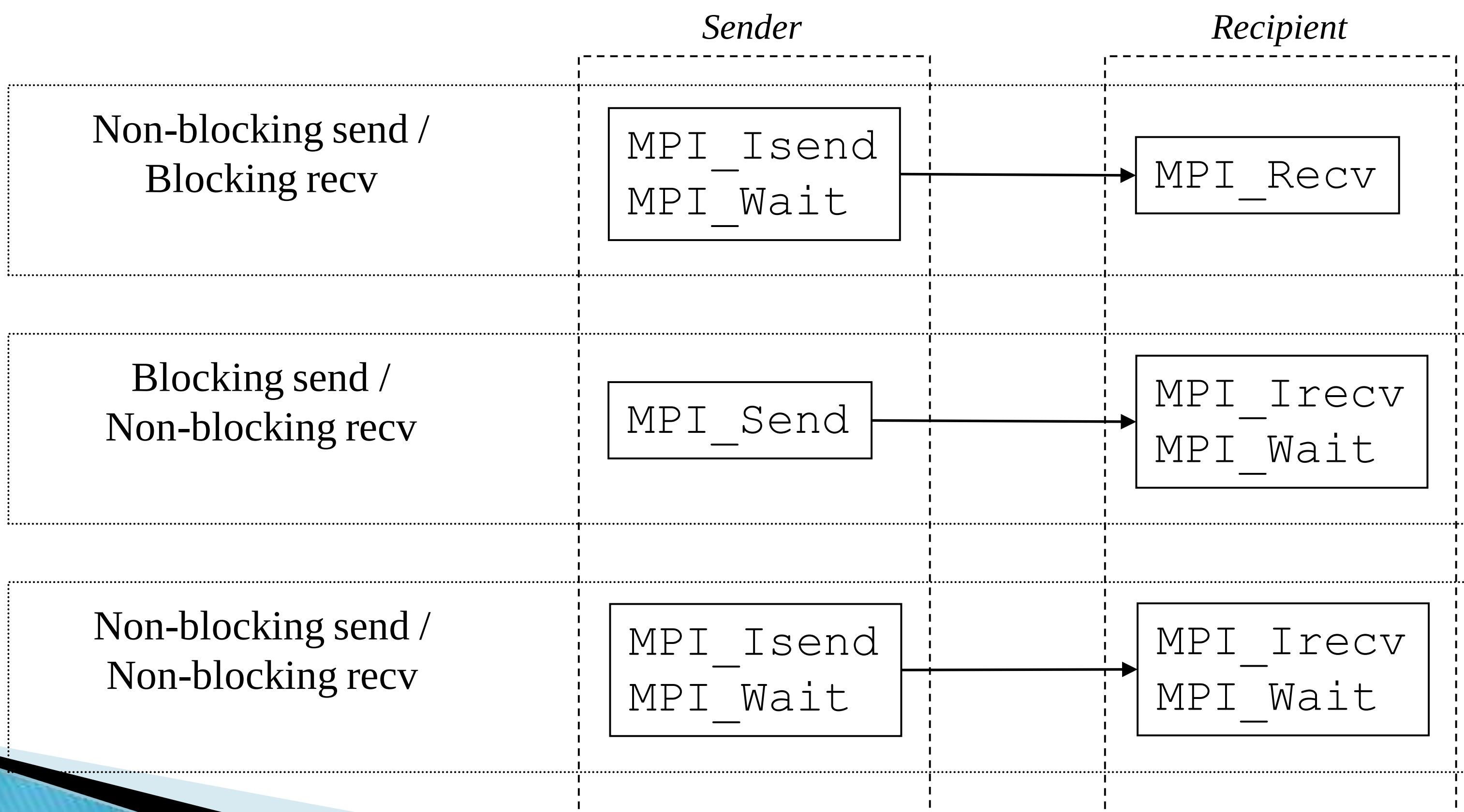
```
int MPI_Irecv (
   void *buf(out),
   int count(in),
   MPI_Datatype datatype(in),
   int source(in),
   int tag(in),
   MPI_Comm comm(in),
   MPI_Request *req(out)
);
```

On additional argument `MPI_Request *req`.

To complete the communication `MPI_Wait` should be called.

Blocking vs. Non-Blocking

- Matching combinations



Non-Blocking Communication

```
int MPI_Test (
  MPI_Request *req(inout),
  int *flag(out),
  MPI_Status *sta(out)
);
```

Write true (non-zero value) in `*flag` if request `*req` is over.

If `*flag` is true, `*req` is assigned to `MPI_REQUEST_NULL` and `*sta` is filled.

If `*flag` is false, values of `*req` and `*sta` are not guaranteed.

Non-Blocking Communication

- Example:

```
MPI_Irecv(msg, N, MPI_BYTE, dest, tag, comm, &req);
do {
instruction1;
…
instructionN;

MPI_Test(&req, &flag, &sta);

} while( !flag );
```

Non-Blocking Communication

```
int MPI_Waitall (
 int nb_req(in),
 MPI_Request *tab_req(inout),
 MPI_Status *tab_sta(out)
);
```

Return when `nb_req` requests located in array `tab_req` are completed.

Status of communications are available as output in array `tab_sta`.

<u>Remark:</u>
Order of communication completion is not important

Non-Blocking Communication

- Example: send/receive with left/right neighbors

```
MPI_Request req[4];
MPI_Status sta[4];

left = (rang + P - 1) % P;
right = (rang + 1) % P;

MPI_Isend(&x[1], 1, MPI_DOUBLE, left, tag, comm, req);
MPI_Isend(&x[N], 1, MPI_DOUBLE, right, tag, comm, req+1);
MPI_Irecv(&x[0], 1, MPI_DOUBLE, left, tag, comm, req+2);
MPI_Irecv(&x[N+1], 1, MPI_DOUBLE, right, tag, comm, req+3);

MPI_Waitall(4, req, sta);
```

Other Available Functions

- MPI proposes multiple functions to complete non-blocking communications

- `MPI_Testall`
  - Test if all requests as input are completed

- `MPI_Waitany` / `MPI_Testany`
  - Wait/Test until at least one request is completed
  - Return index of completed request

- `MPI_Waitsome` / `MPI_Testsome`
  - Wait/Test until at least one request is completed
  - Return set of completed requests

Communications and modes

- Non-blocking communication is different from asynchronous
- Non-blocking communications can be done in different modes: synchronous, buffered or regular

Type/Mode	Standard	Buffered	Synchronous
Blocking	MPI_Send	MPI_Bsend	MPI_Ssend
Non-Blocking	MPI_Isend	MPI_Ibsend	MPI_Issend

MPI Point-to-Point Communications

- Checking Incoming Messages

Checking Incoming Messages

- How to receive a message without knowing the actual final size?
  - MPI_Recv function requires an upper bound on incoming messages
    - MPI_Recv is not appropriate if message size is unknown
  - MPI proposes function to retrieve information on incoming messages before performing the receive actions: MPI_Iprobe and MPI_Probe

Checking Incoming Messages

```
int MPI_Iprobe (
  int source(in),
  int tag(in),
  MPI_Comm comm(in),
  int *flag(out),
  MPI_Status *sta(out)
);
```

Check if a message coming from `source` with label `tag` has arrived (`MPI_ANY_SOURCE` and `MPI_ANY_TAG` are allowed).

Return true (non-zero value) in `*flag` such a message exists.

In such case, status of incoming message is provided in `*sta` .

Checking Incoming Messages

```
int MPI_Probe (
   int source(in),
   int tag(in),
   MPI_Comm comm(in),
   MPI_Status *sta(out)
);
```

Wait for a message coming from sender `source` with label `tag` has arrived (`MPI_ANY_SOURCE` and `MPI_ANY_TAG` are allowed).

Upon return, status is written in `*sta`.

Receiving messages after `MPI_Iprobe/MPI_Probe`

- Calls to `MPI_Iprobe` and `MPI_Probe` check incoming messages or wait for a specific message to come.
  - But they do not perform the actual reception

- To receive the target message:
  1. Call `MPI_Get_count` to get the message size
  2. Allocate a buffer corresponding to this size
  3. Call `MPI_Recv` to receive the message

Receiving messages after `MPI_Iprobe/MPI_Probe`

```
MPI_Status sta;
int size, done;
do {
instruction1;
…
instructionN;
MPI_Iprobe(MPI_ANY_SOURCE, MPI_ANY_TAG, MPI_COMM_WORLD, &done, &sta);
} while (!done);

MPI_Get_count(&sta, MPI_BYTE, &size);
char *buf = malloc( size );
MPI_Recv(buf, size, MPI_BYTE, sta.MPI_SOURCE, sta.MPI_TAG,
MPI_COMM_WORLD, &sta);
```