MPI
part 1

CSC 5001

Octobre 2018

Credits

These slides were originaly created by Patrick Carribault from CEA as part of INF560 (Algorithmique Parallèle et Distribuée) at Ecole Polytechnique. They were (slightly) adapted to fit this class format.

Lecture Outline

- **Parallel programming**
- **Introduction to MPI**
  - Compilation & execution
  - Main organization
- **Point-to-point communications**

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

- 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
- 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
- OpenMP, pthread, TBB, Cilk, ...

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
- On distributed-memory system
  - Easy
  - Processes on such systems have to exchange messages which is included in distributed-memory model
- 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 segment to improve communication performance
- PVM, MPI

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

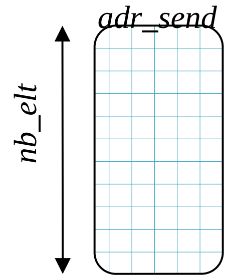
T0 Task	**T1 Task**
instruction1; *instruction2;*	*instruction1;* *instruction2;*

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

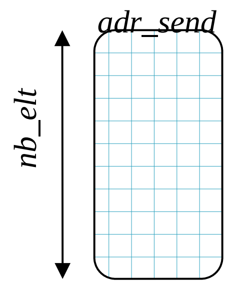
instruction1;
instruction2;

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

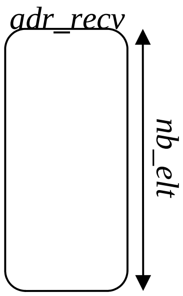
instruction1;
instruction2;
send(*adr_send*, *nb_elt*, **T1**);



T1 Task

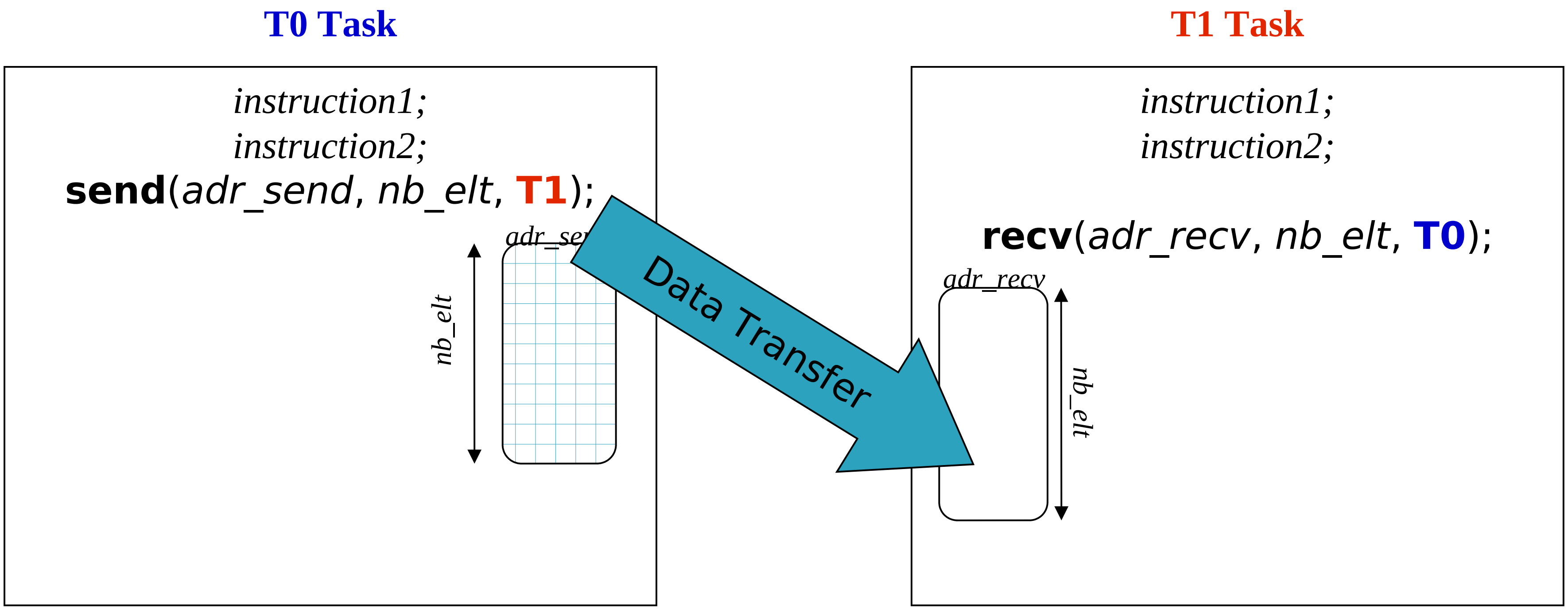
instruction1;
instruction2;

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
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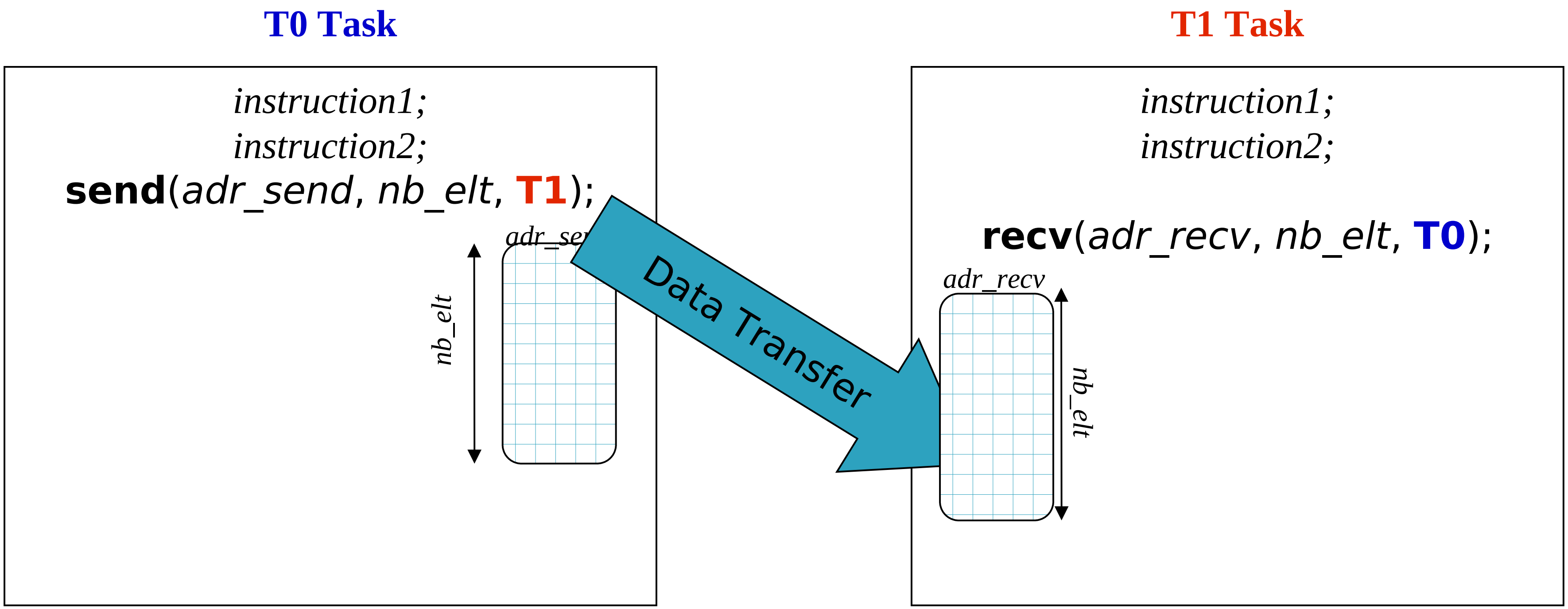
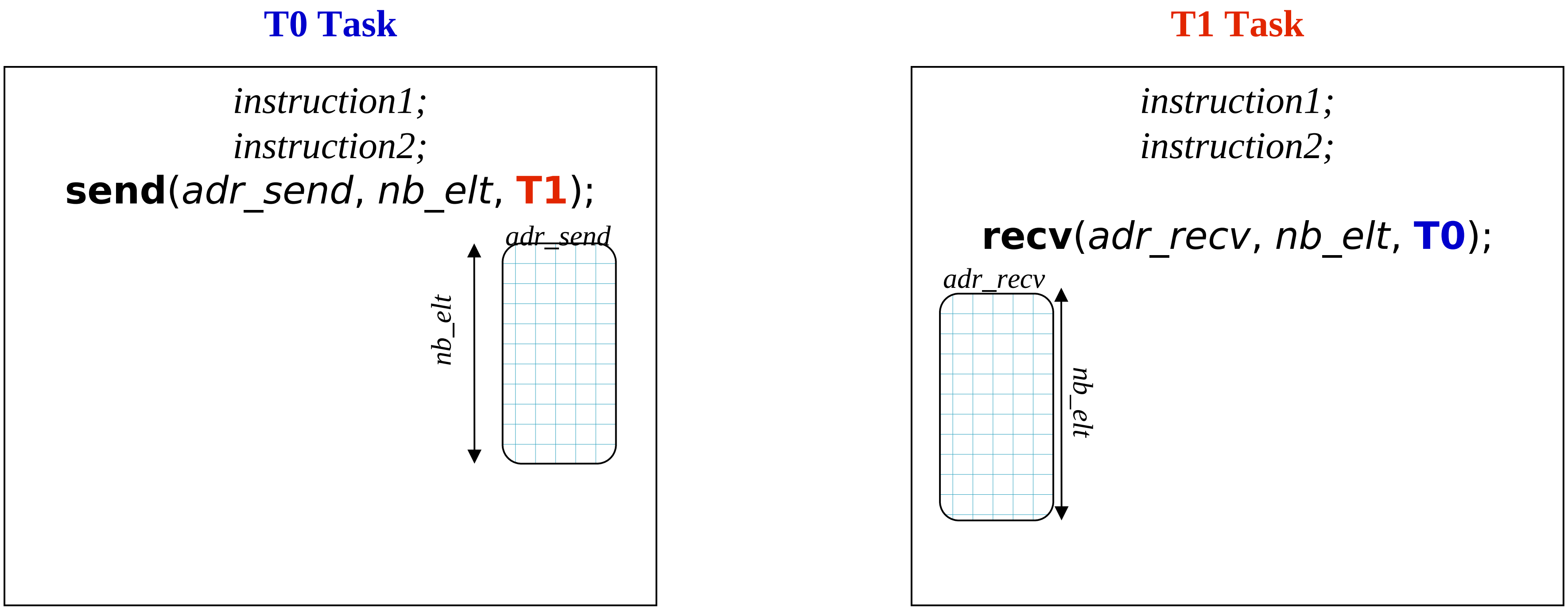


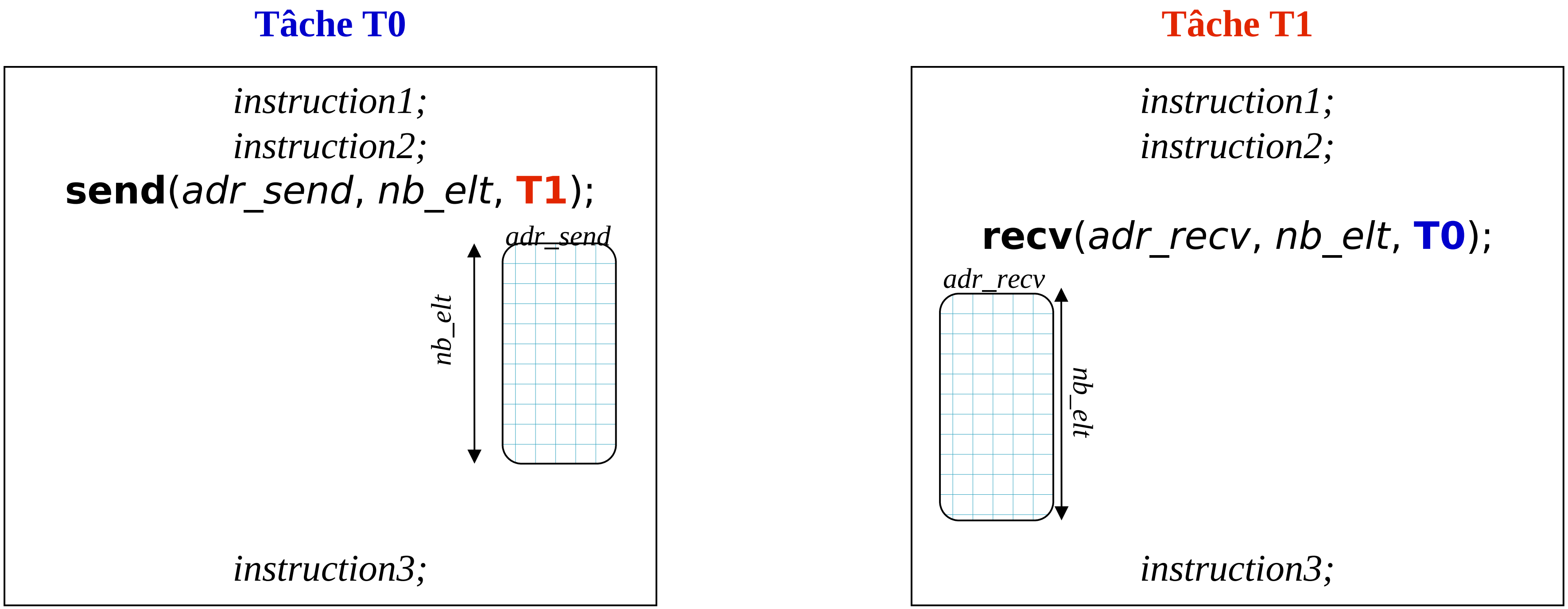
Main Principle

- T1 owns a complete copy of data sent by T0



Main Principle

- Tasks T0 and T1 may continue their execution
- Following instructions of T1 may access to data stored at address *adr_recv*



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

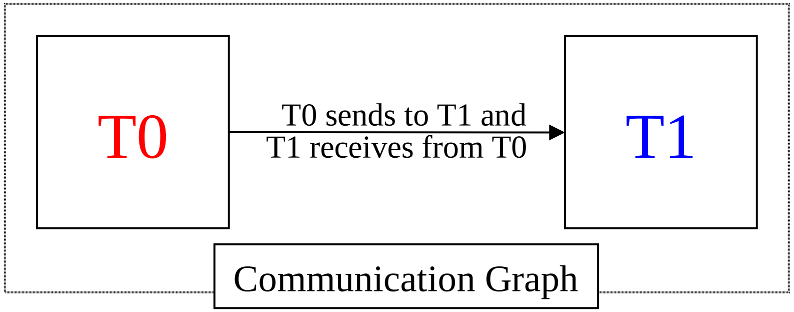
T1

```
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);
```

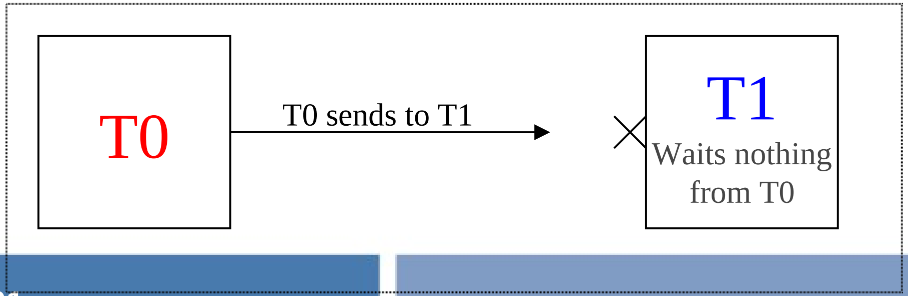
T1 needs partial sum from T0

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
  - Multithreading
  - Parallel I/O
- MPI 3.0 adds
  - Non-blocking collective communications
- Lots of features!
  - 120 functions in MPI 1
  - More than 200 for MPI 2

Hello World!

```c
#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>
- Complex way
  - Use a standard compiler, and pass lots of options

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

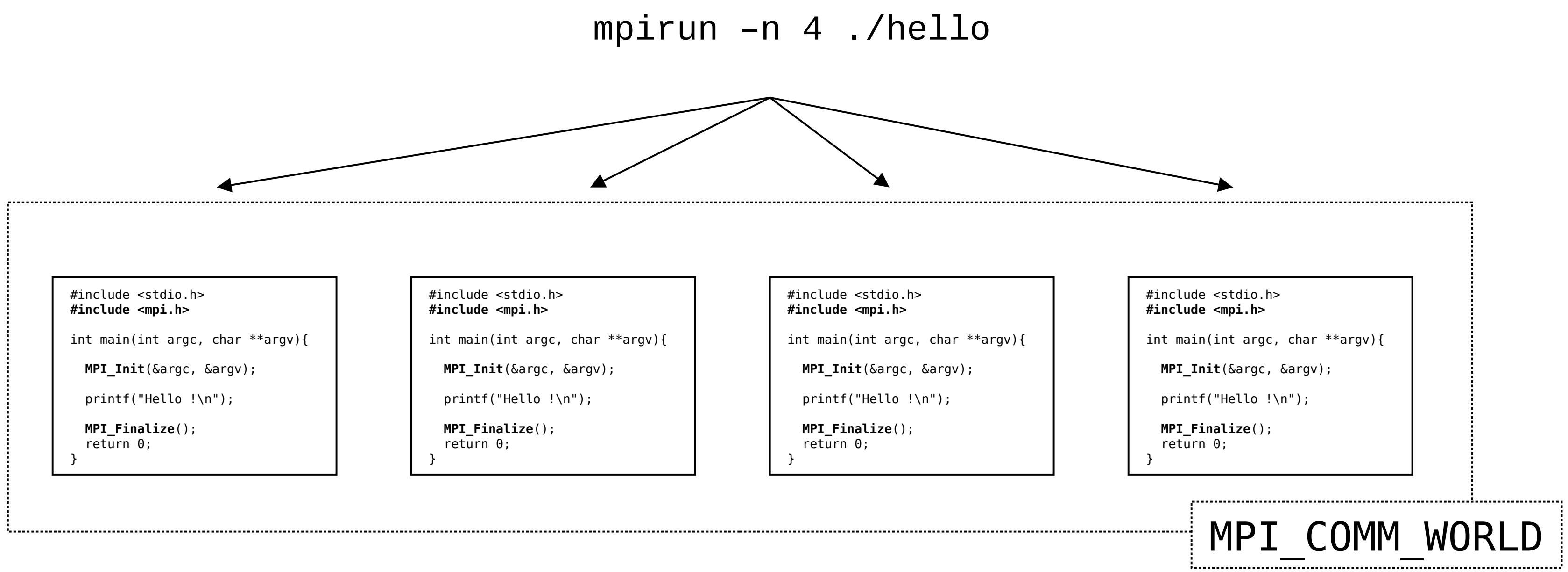
Execution

- mpirun can spawn MPI processes
  - Connect on machines
  - Create network connections

```
$ mpirun -n 4 -f machines ./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
  - « machines » contains a list of machines

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

```
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

```
#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;
}
```

```
$ mpirun  –n 4  ./a.out
Number of processes = 4
Number of processes = 4
Number of processes = 4
Number of processes = 4
```

Process Rank

- 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);
```

```
#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;
}
```

```
$ mpirun –n 4  ./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 different from number of available cores/processors!

- 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)
      );
```

Main characteristics of message to send (buf, count, datatype)

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.

Remarks on Sending Messages

- `MPI_Send` is a 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 (buf, count, datatype)

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.

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

```
int main(int argc, char **argv) {
  double p = 0., s0;
  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++ )
    p += tab[i];

  tag = 1000; /* Message tag */
  if (r == 0) {
    /* Rank 0 */
    MPI_Send(&p, 1, MPI_DOUBLE, 1, tag, MPI_COMM_WORLD);
  } else {
    /* Rank 1 */
    MPI_Recv(&s0, 1, MPI_DOUBLE, 0, tag, MPI_COMM_WORLD, &status);
    printf( "Sum = %d\n", s0+p );
  }
  MPI_Finalize();
  return 0;
}
```

Simple MPI Example

```
/* … */
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(&som, 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!

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

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

T0

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

T1

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

- 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 return only when the message has been received and processed

Blocking Communications

- 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

T0

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

T1

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

MPI Point-to-Point Communications

Non-Blocking Communications

Non-Blocking Communication

- Definition
  - A **non-blocking** communication has not guarantee when send 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).

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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 finished 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 progresses

- 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 finish the communication `MPI_Wait` should be called.

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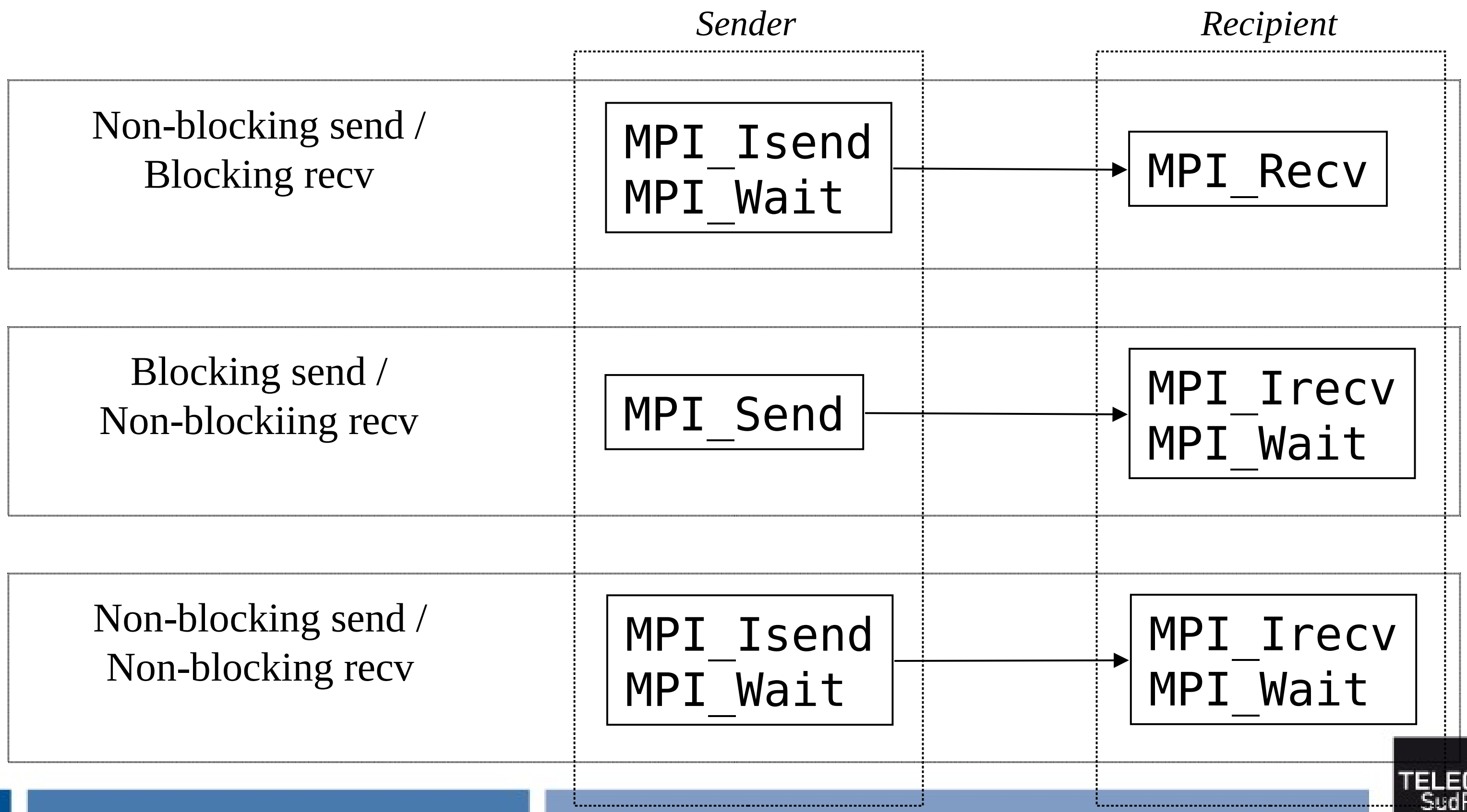
Blocking vs. Non-Blocking

- 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 is 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