Introduction to Parallel Computing (CMSC416 / CMSC616)

Message Passing and MPI

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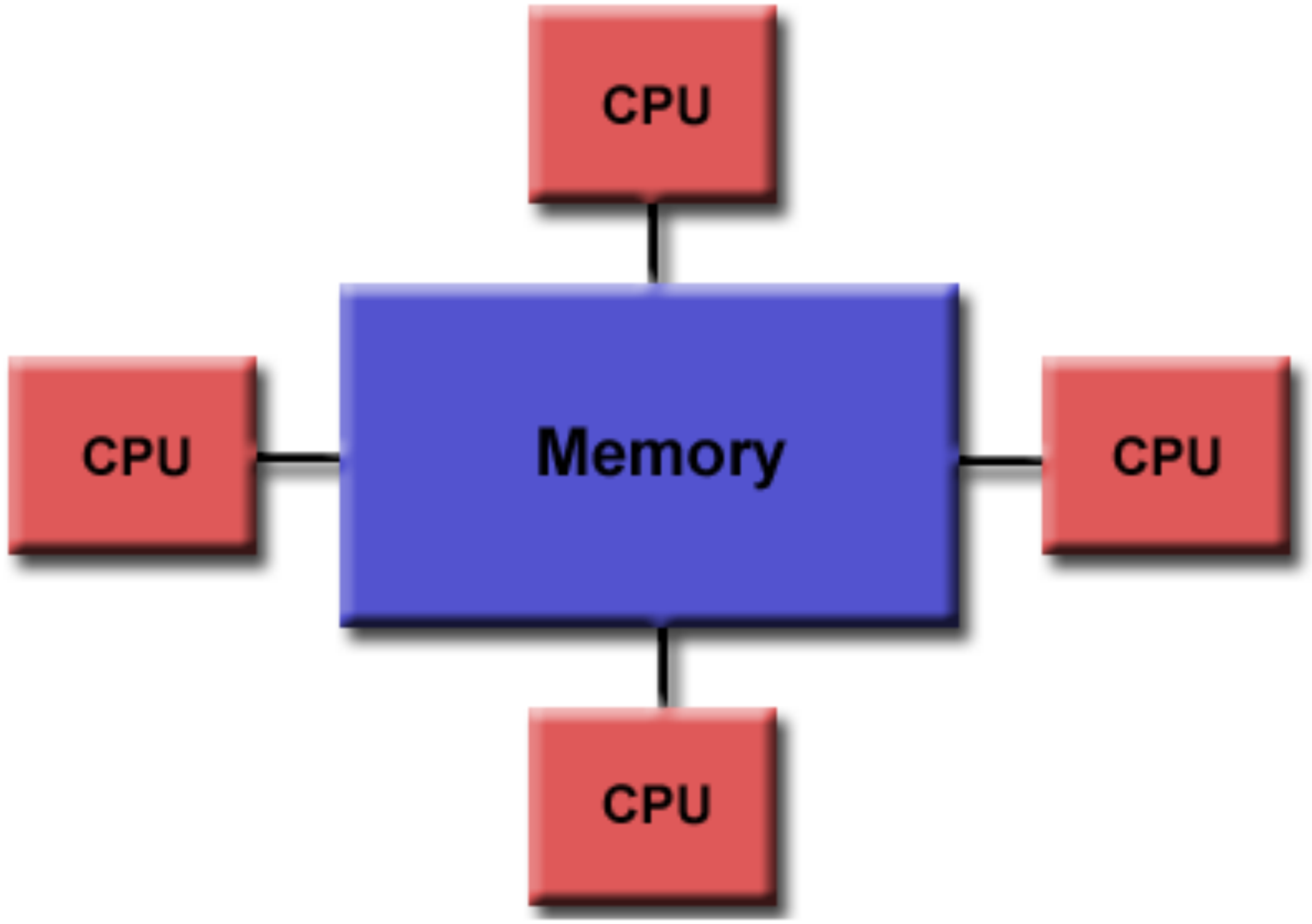
Announcements

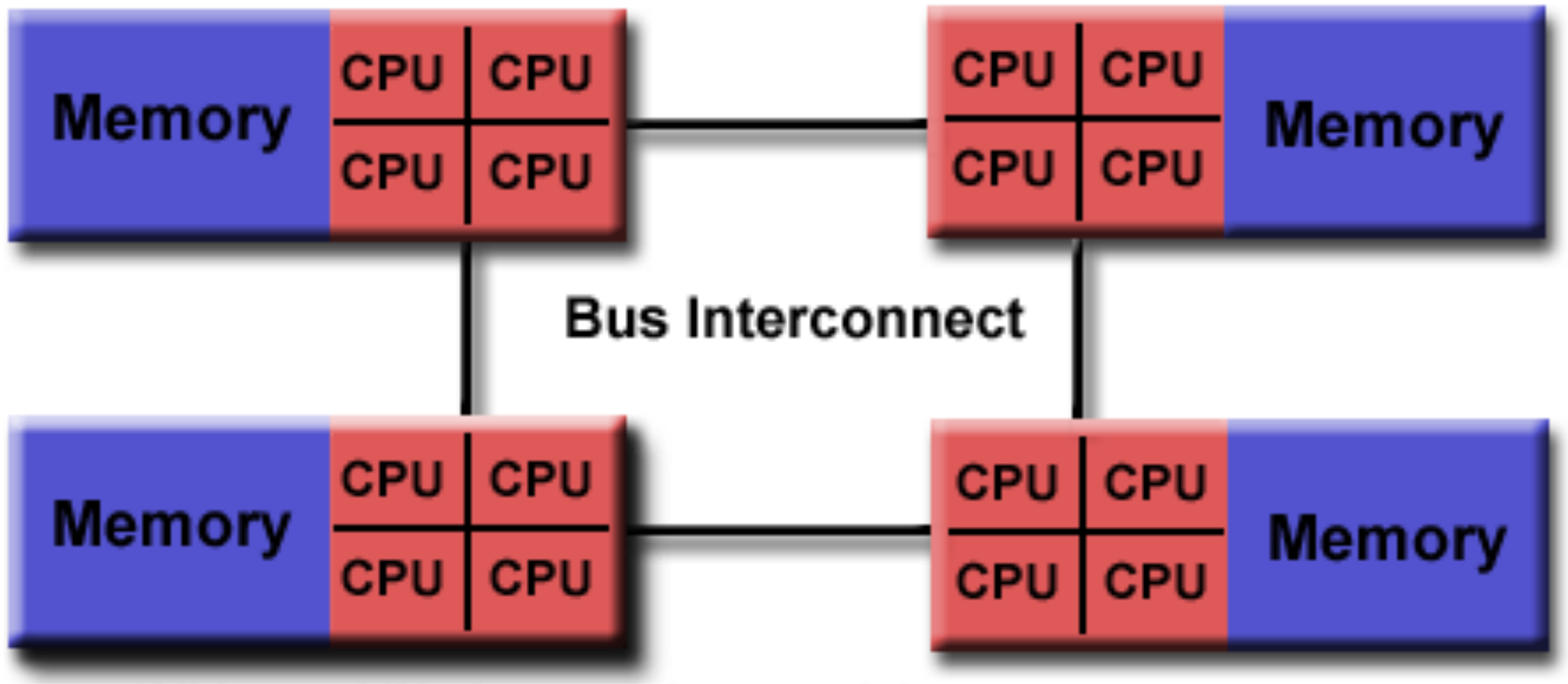
- Assignment 0 is now posted online.
  - Due on: Sept 18, 2023 11:59 pm
- Assignment 1 will be posted on Sept 18
- Resources for learning MPI:
  - https://mpitutorial.com
  - https://rookiehpc.org

Shared memory architecture

- All processors/cores can access all memory as a single address space



Uniform Memory Access

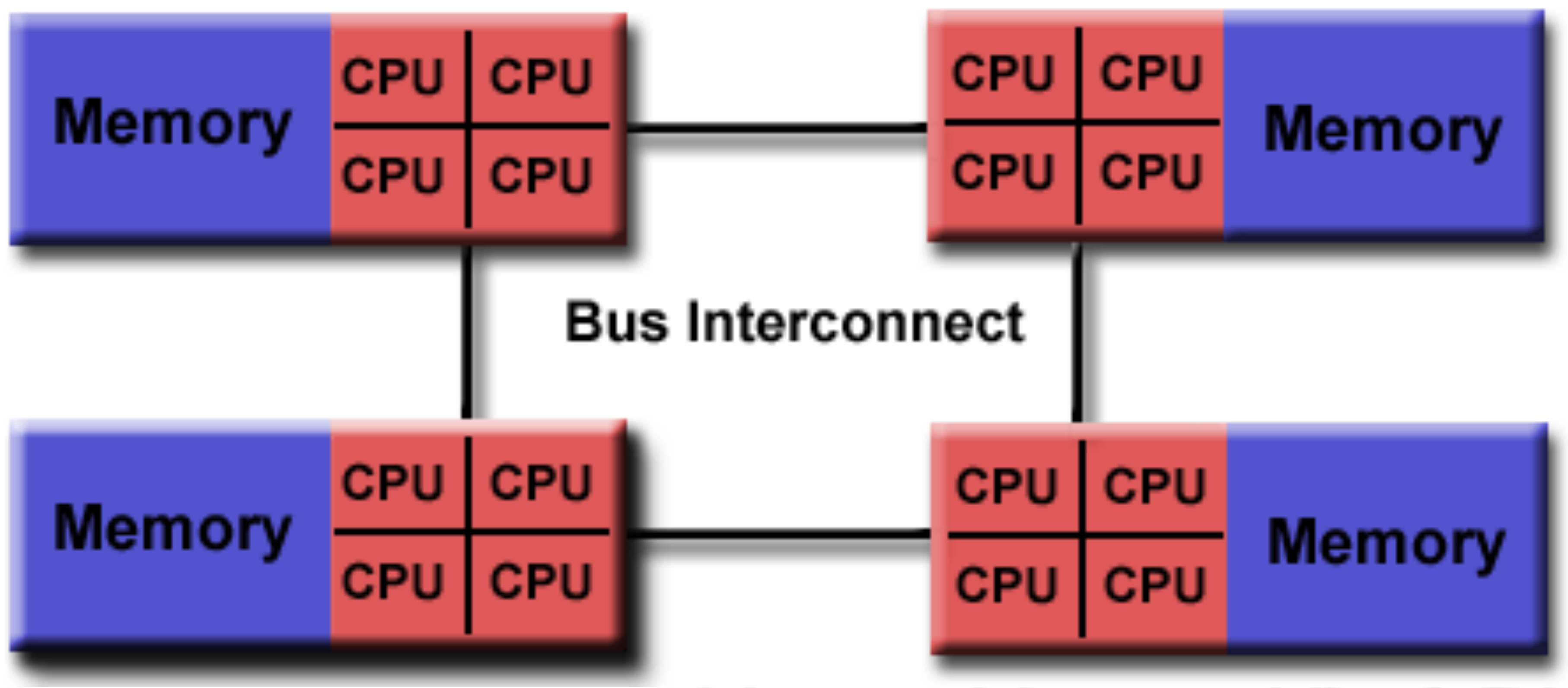


Non-uniform Memory Access (NUMA)

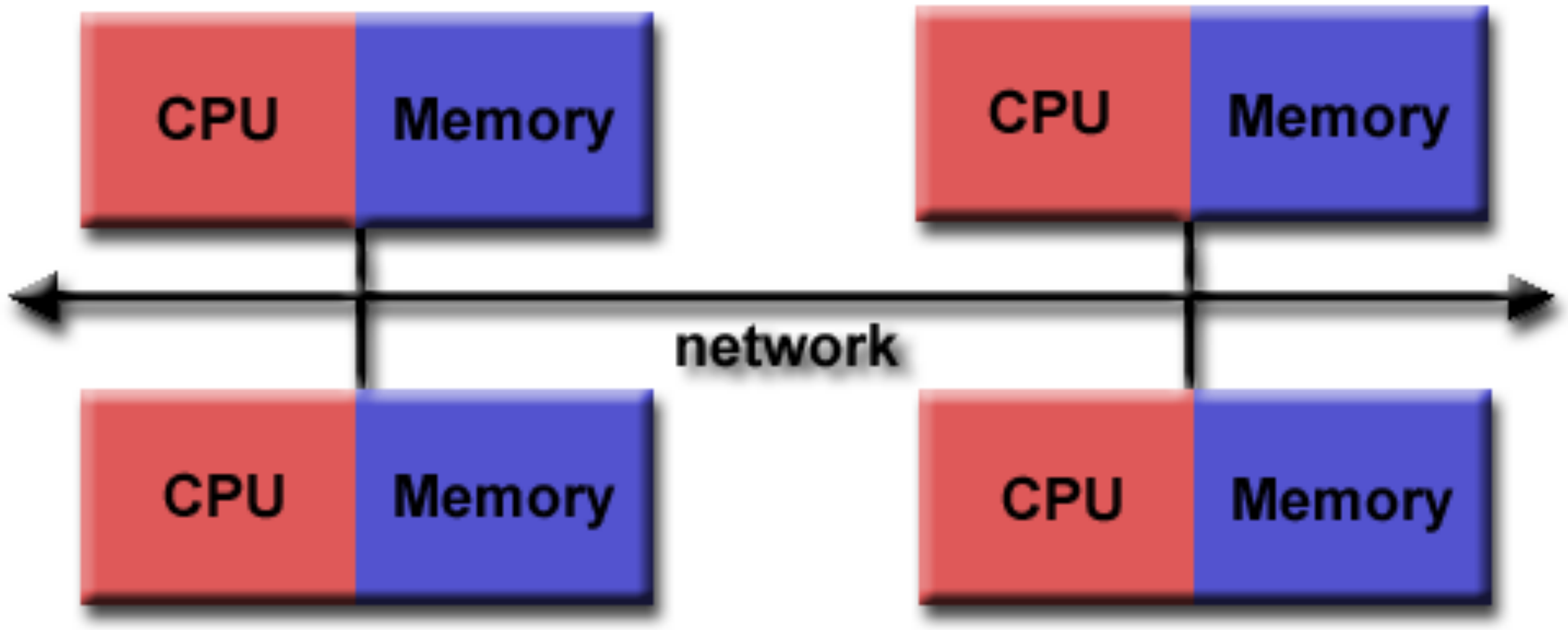
https://computing.llnl.gov/tutorials/parallel_comp/#SharedMemory

Distributed memory architecture

- Each processor/core only has access to its local memory
- Writes in one processor's memory have no effect on another processor's memory



Non-uniform Memory Access (NUMA)



Distributed memory

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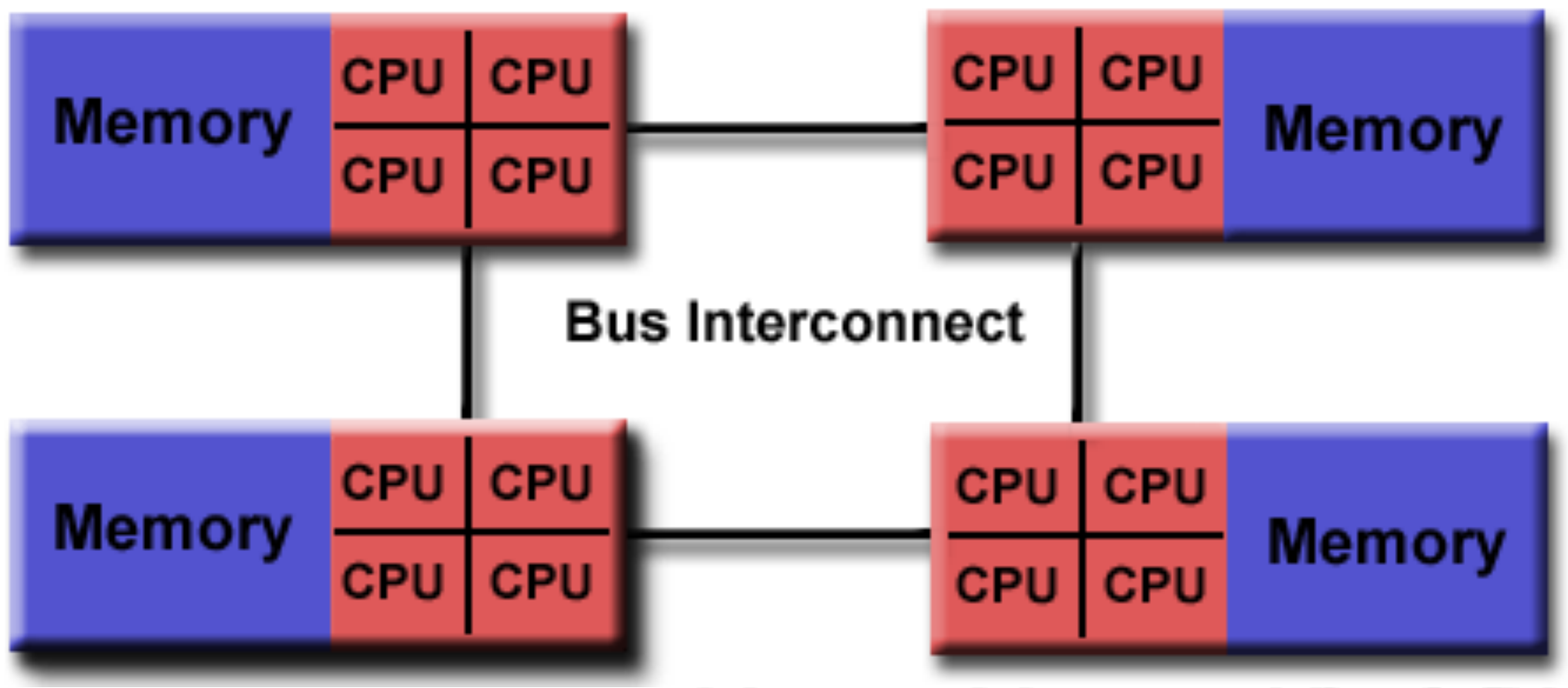

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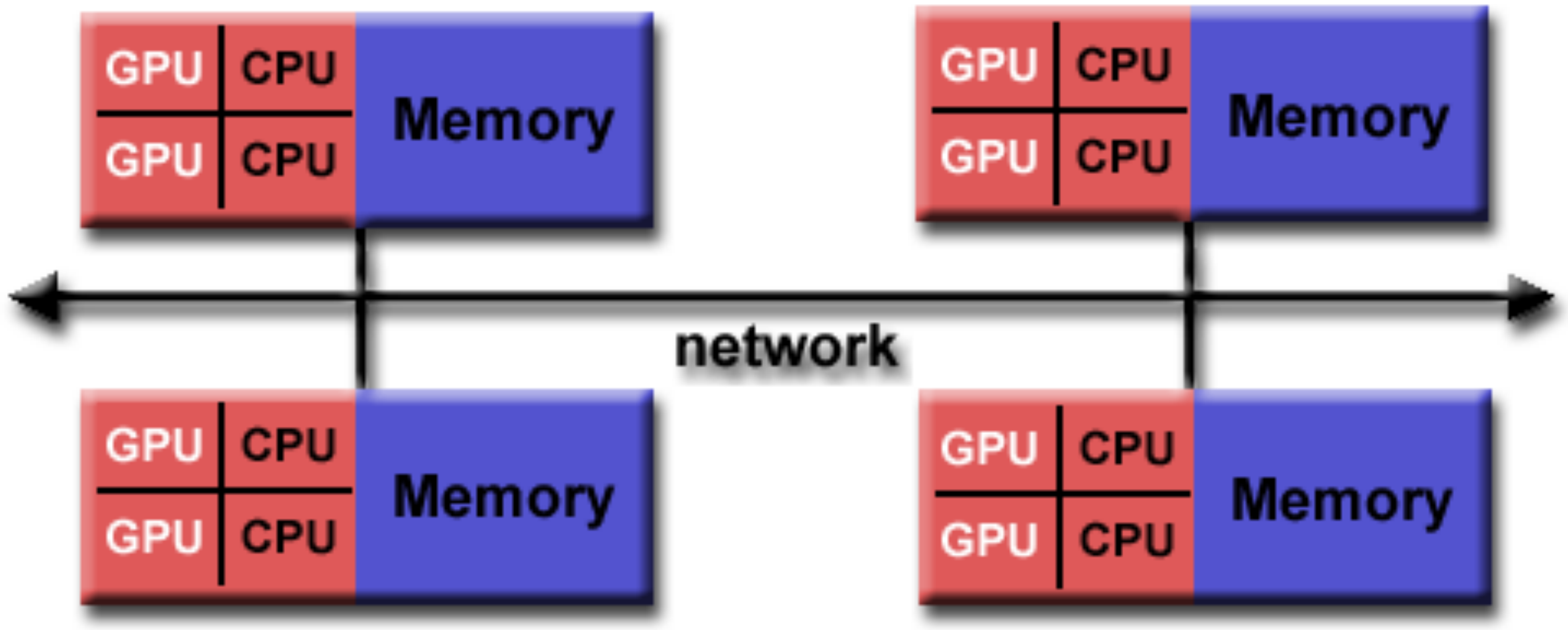


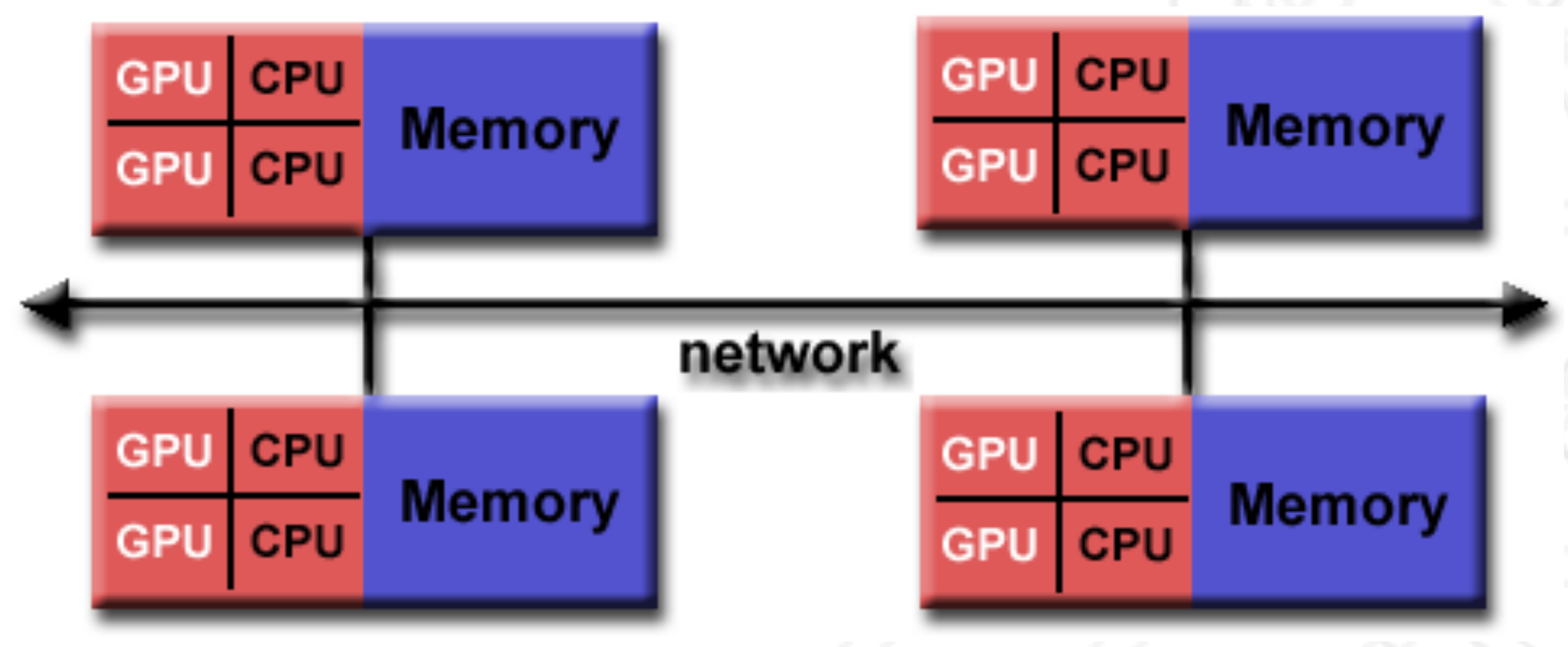
Distributed memory

Programming models

- Shared memory model: All threads have access to all of the memory
  - pthreads, OpenMP
- Distributed memory model: Each process has access to its own local memory
  - Also sometimes referred to as message passing
  - MPI, Charm++
- Hybrid models: Use both shared and distributed memory models together
  - MPI+OpenMP, Charm++ (SMP mode)

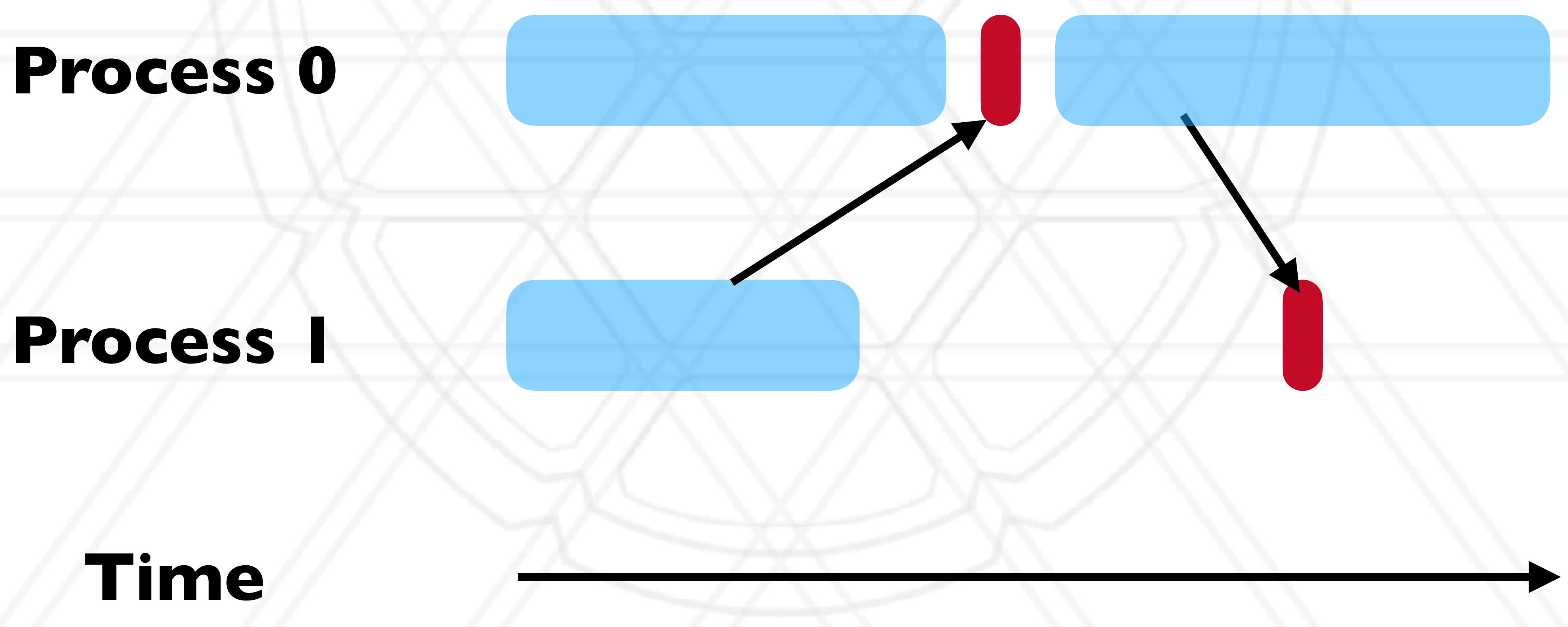
Distributed memory programming models

- Each process only has access to its own local memory / address space
- When it needs data from remote processes, it has to send/receive messages



Message passing

- Each process runs in its own address space
  - Access to only their memory (no shared data)
- Use special routines to exchange data



Message passing programs

- A parallel message passing program consists of independent processes
  - Processes created by a launch/run script
- Each process runs the same executable, but potentially different parts of the program, and on different data
- Often used for SPMD style of programming

Message passing history

- PVM (Parallel Virtual Machine) was developed in 1989-1993
- MPI forum was formed in 1992 to standardize message passing models and MPI 1.0 was released in 1994
    - v2.0 — 1997
    - v3.0 — 2012
    - v4.0 — 2021

Message Passing Interface (MPI)

- It is an interface standard — defines the operations / routines needed for message passing
- Implemented by vendors and academics for different platforms
  - Meant to be "portable": ability to run the same code on different platforms without modifications
- Some popular open-source dimplementations are MPICH, MVAPICH, OpenMPI
  - Vendors often implement their own versions optimized for their hardware: Cray/HPE, Intel

Hello world in MPI

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

int main(int argc, char *argv[]) {
  int rank, size;
  MPI_Init(&argc, &argv);

  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
  MPI_Comm_size(MPI_COMM_WORLD, &size);
  printf("Hello world! I'm %d of %d\n", rank, size);

  MPI_Finalize();
  return 0;
}
```

Compiling and running an MPI program

- Compiling:

```
mpicc -o hello hello.c
```

- Running:

```
mpirun -n 2 ./hello
```

Process creation / destruction

- `int MPI_Init( int argc, char **argv )`
  - Initializes the MPI execution environment
- `int MPI_Finalize( void )`
  - Terminates MPI execution environment

Process identification

- `int MPI_Comm_size( MPI_Comm comm, int *size )`
  - Determines the size of the group associated with a communicator
- `int MPI_Comm_rank( MPI_Comm comm, int *rank )`
  - Determines the rank (ID) of the calling process in the communicator
- Communicator — a set of processes identified by a unique tag
  - Default communicator: `MPI_COMM_WORLD`

Send a message

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

`buf`: address of send buffer

`count`: number of elements in send buffer

`datatype`: datatype of each send buffer element

`dest`: rank of destination process

`tag`: message tag

`comm`: communicator

Receive a message

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

`buf`: address of receive buffer

`status`: status object

`count`: maximum number of elements in receive buffer

`datatype`: datatype of each receive buffer element

`source`: rank of source process

`tag`: message tag

`comm`: communicator

MPI_Status object

- Represents the status of the received message
- count: number of received entries
- MPI_SOURCE: source of the message
- MPI_TAG: tag value of the message
- MPI_ERROR: error associated with the message

```
typedef struct _MPI_Status {
  int count;
  int cancelled;
  int MPI_SOURCE;
  int MPI_TAG;
  int MPI_ERROR;
} MPI_Status, *PMPI_Status;
```

Semantics of point-to-point communication

- A receive *matches* a send if the arguments to the calls match
  - Same communicator and tag
  - If the datatypes and count don't match, the results could be disastrous
- If a sender sends two messages to a destination, and both match the same receive, the second message cannot be received if the first is still pending
  - "No-overtaking" messages
  - Always true when processes are single-threaded
- Tags can be used to disambiguate between messages in case of non-determinism

Simple send/receive in MPI

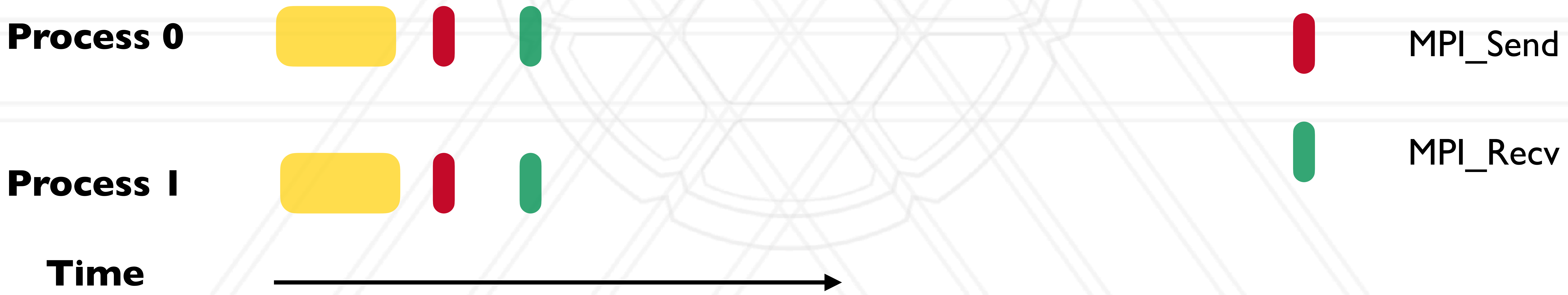
```
int main(int argc, char *argv[]) {
  ...
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
  MPI_Comm_size(MPI_COMM_WORLD, &size);

  int data;
  if (rank == 0) {
    data = 7;
    MPI_Send(&data, 1, MPI_INT, 1, 0, MPI_COMM_WORLD);
  } else if (rank == 1) {
    MPI_Recv(&data, 1, MPI_INT, 0, 0, MPI_COMM_WORLD, MPI_STATUS_IGNORE);
    printf("Process 1 received data %d from process 0\n", data);
  }

  ...
}
```

Basic MPI_Send and MPI_Recv

- MPI_Send and MPI_Recv routines are blocking
  - Only return when the buffer specified in the call can be used again
  - Send: Returns once sender can reuse the buffer
  - Recv: Returns once data from Recv is available in the buffer



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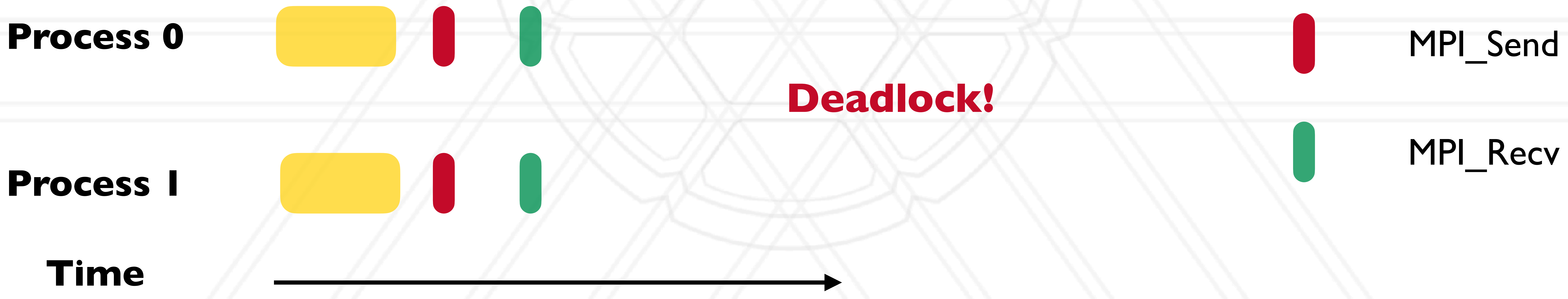

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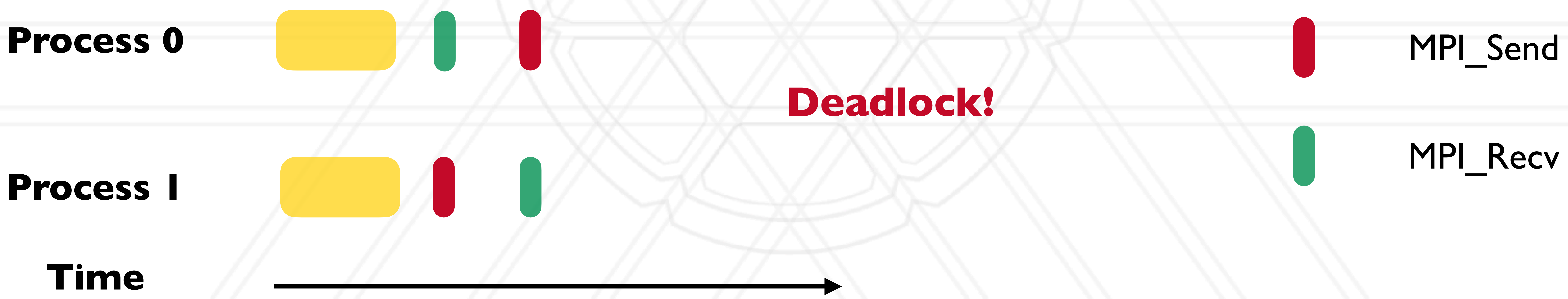

Example program

```
int main(int  argc, char *argv[]) {
  ...
  MPI_Comm_rank(MPI_COMM_WORLD, &rank);
  ...
  if (rank % 2 == 0) {
    data = rank;
    MPI_Send(&data, 1, MPI_INT, rank+1, 0, ...);
  } else {
    data = rank * 2;
    MPI_Recv(&data, 1, MPI_INT, rank-1, 0, ...);

    ...
    printf("Process %d received data %d\n”, data);
  }
  ...
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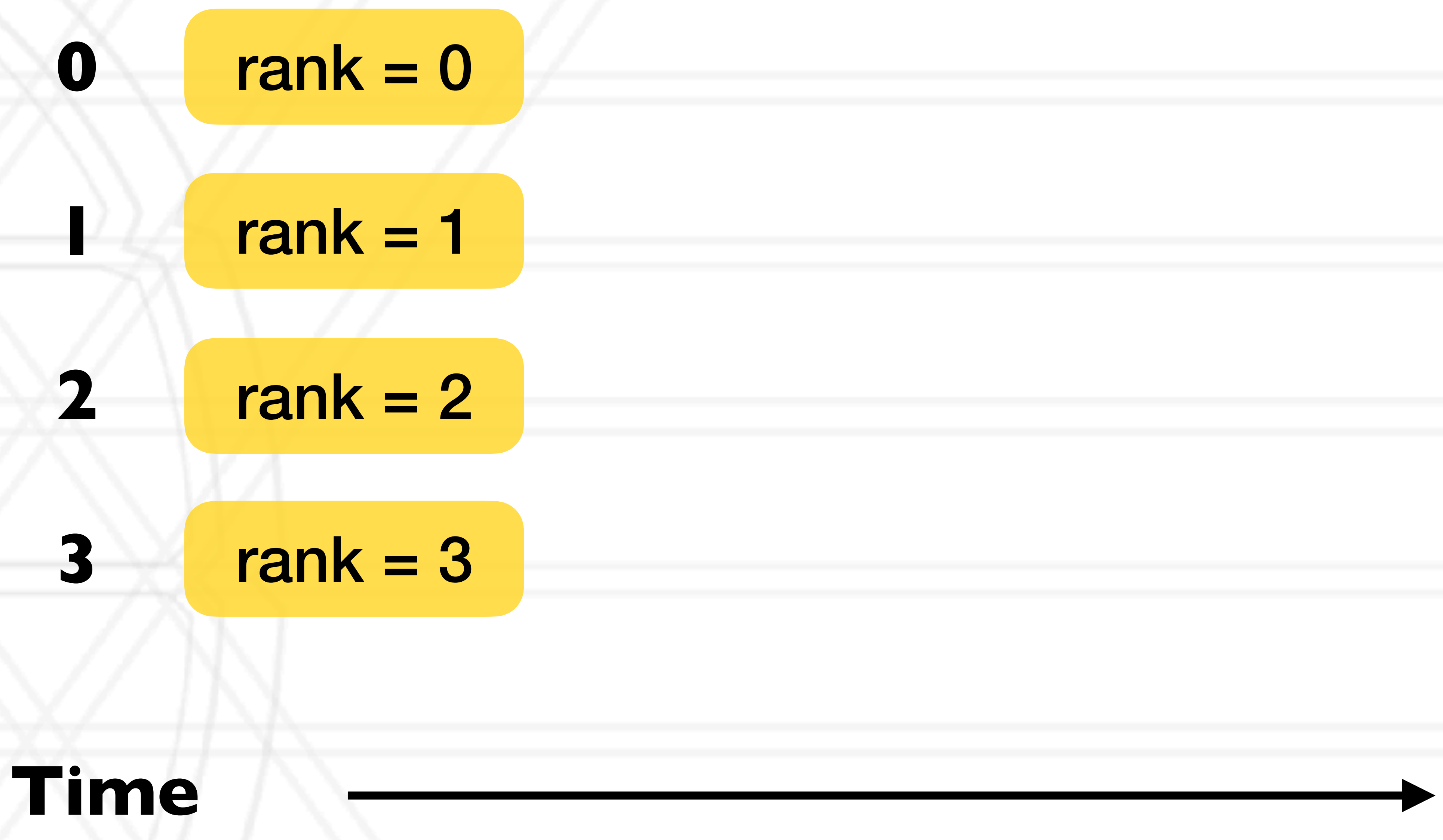

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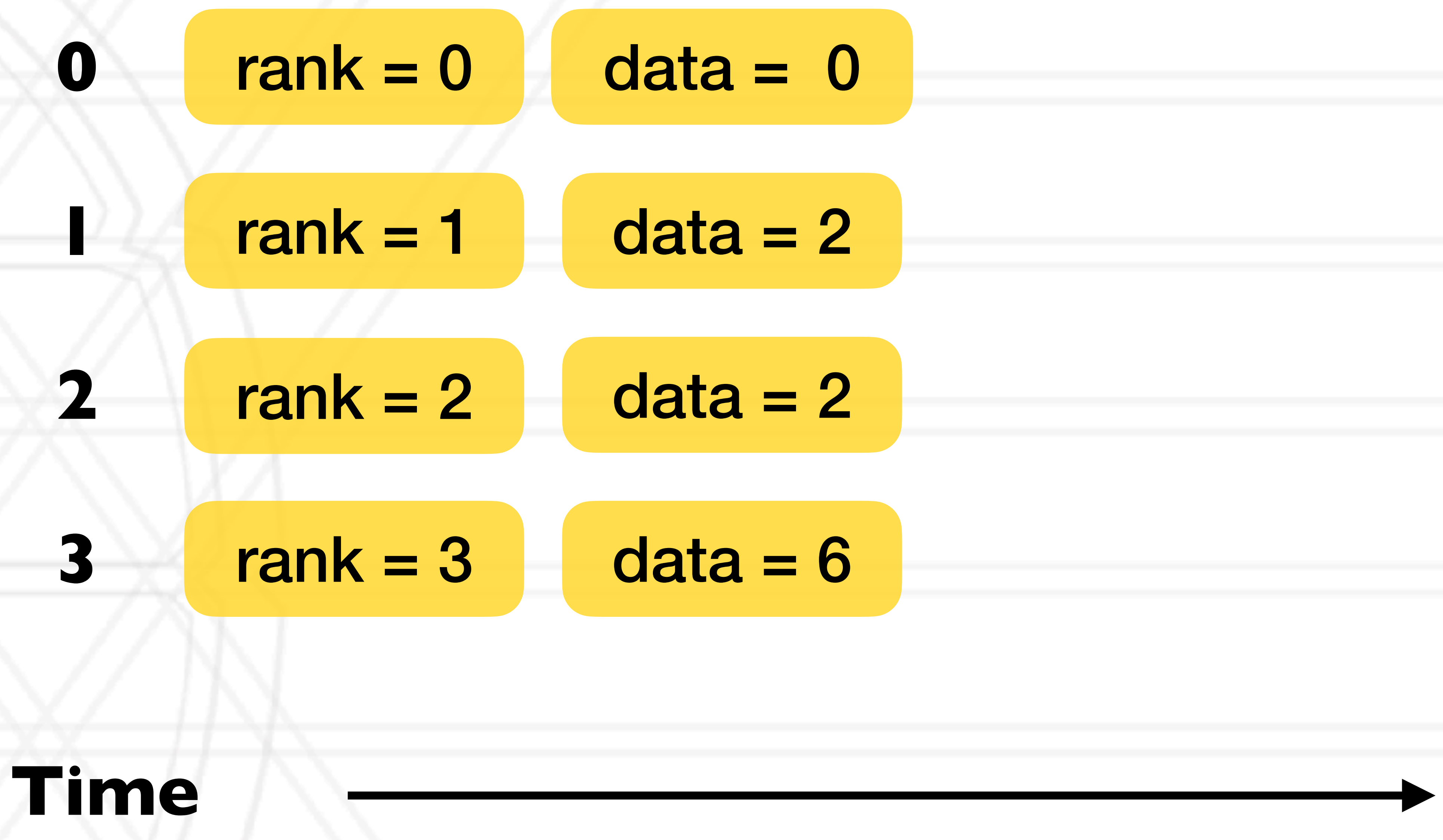

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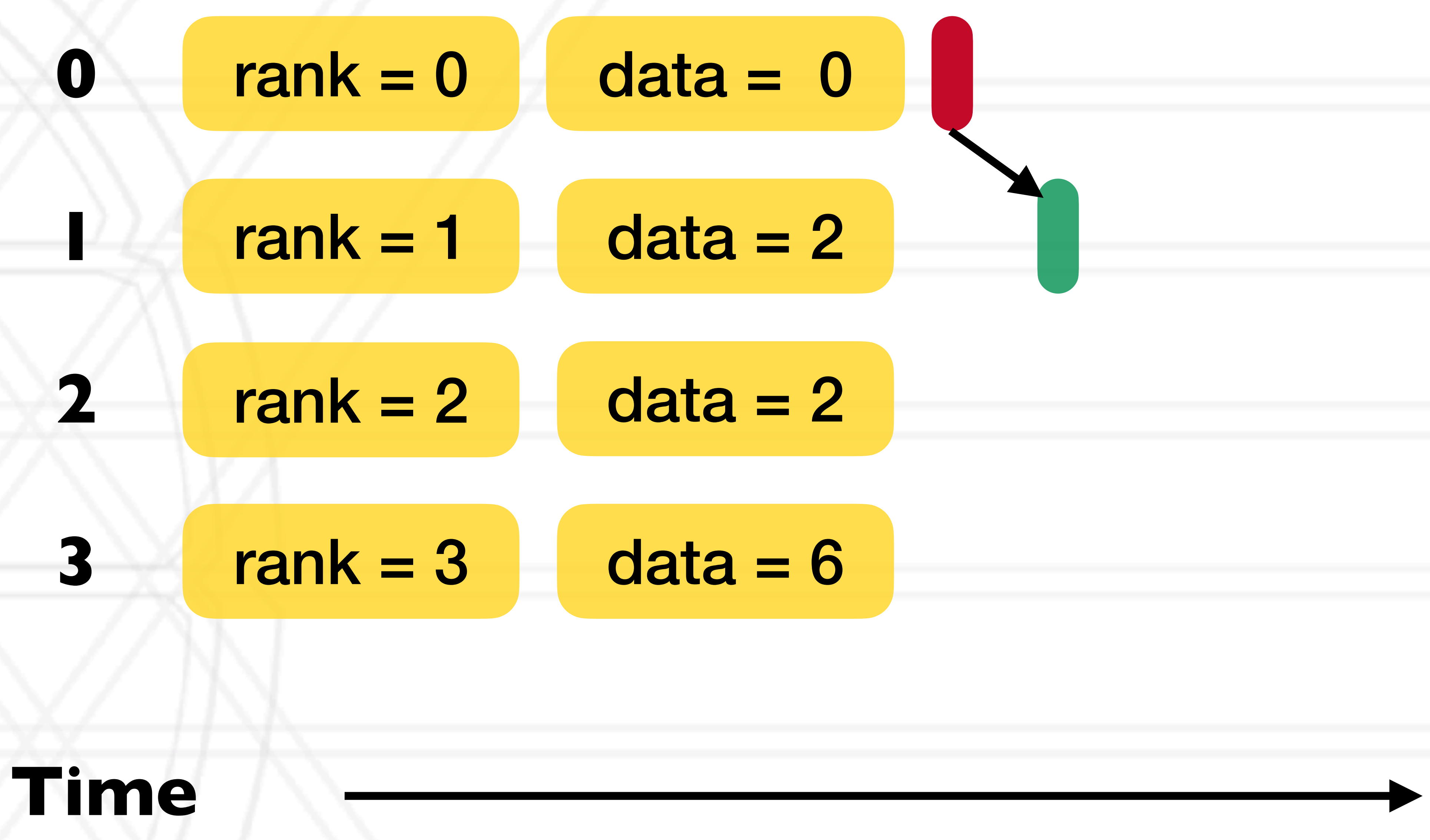

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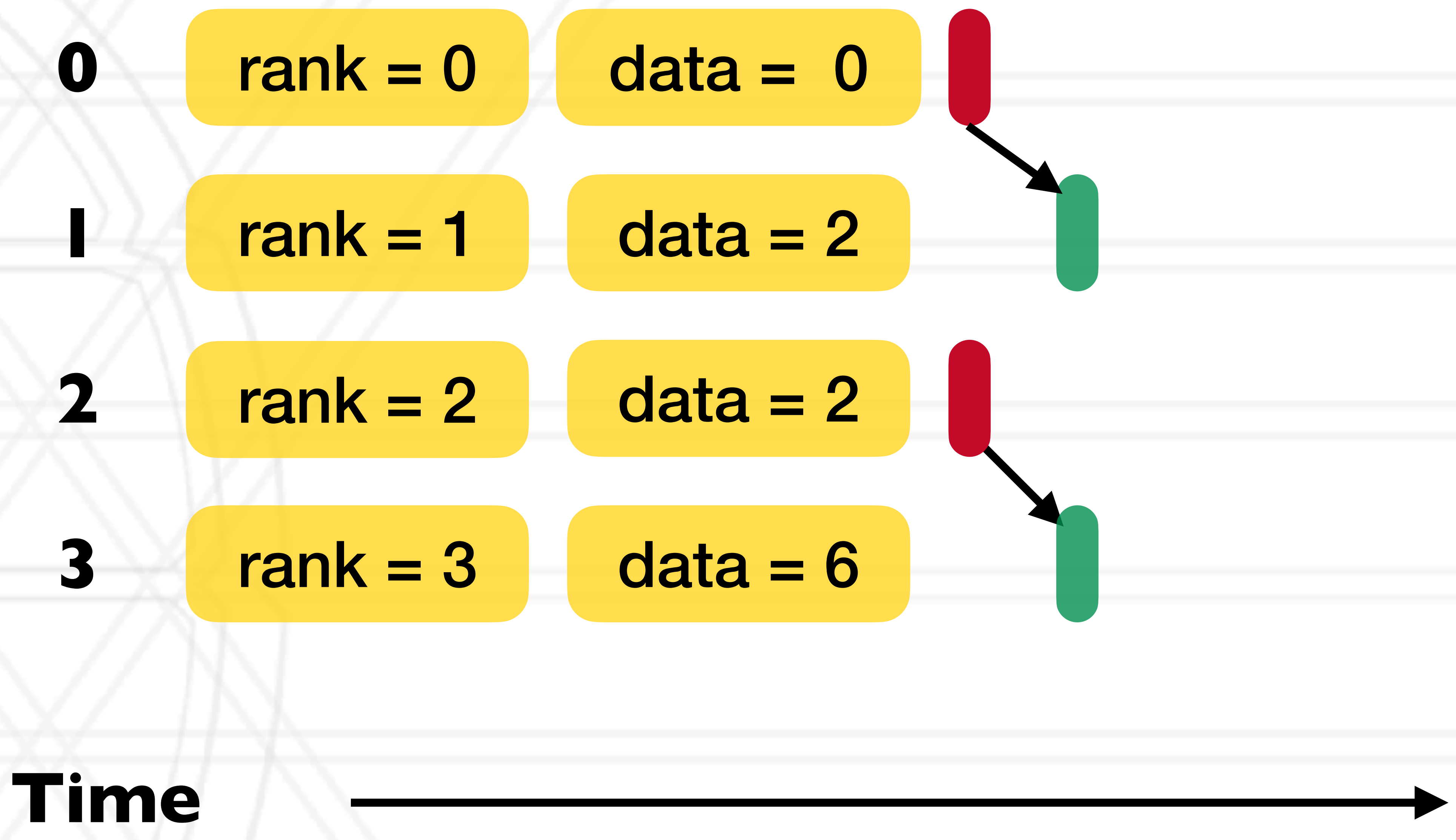

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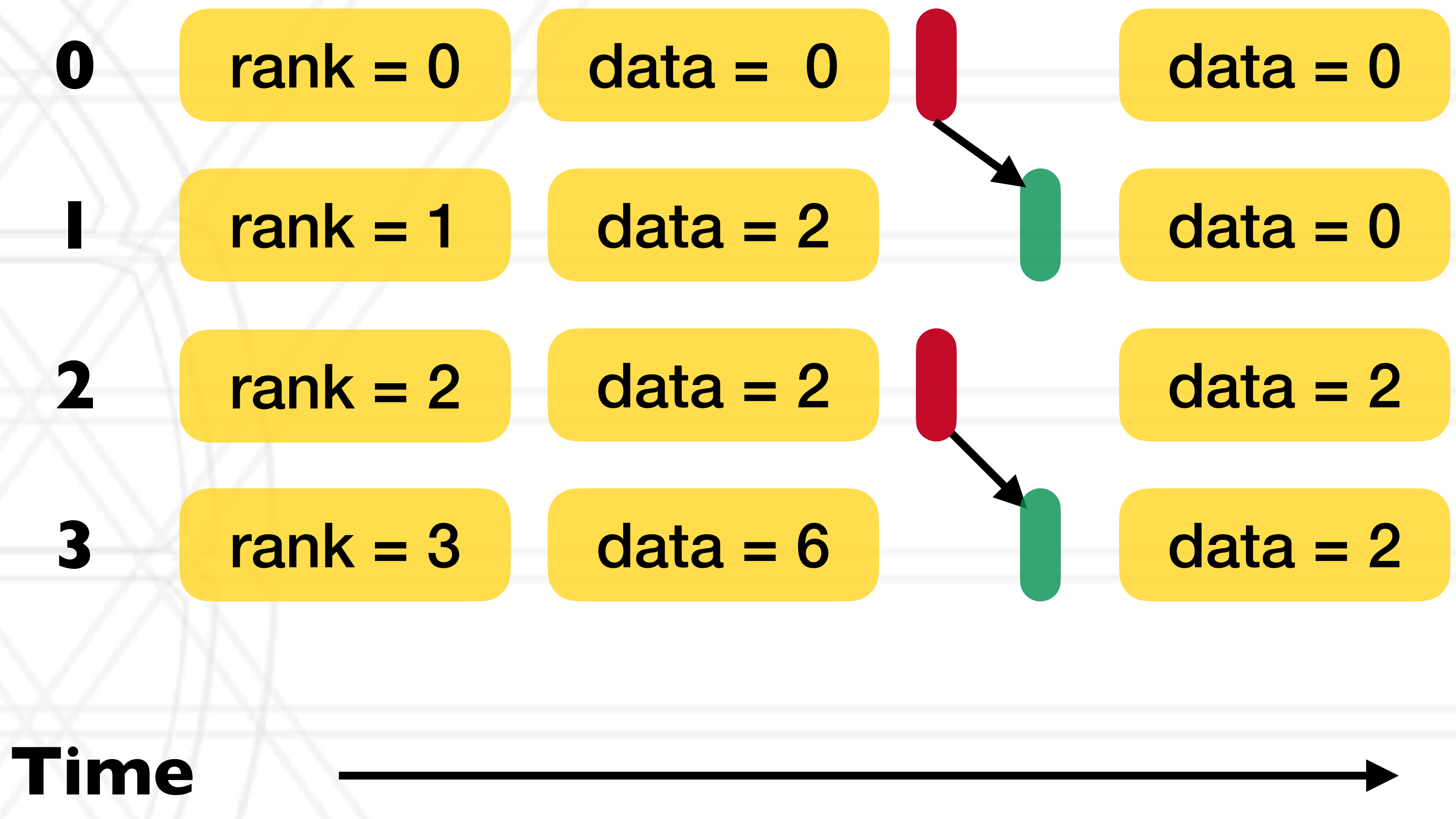

MPI communicators

- Communicator represents a group or set of processes numbered 0, … , n-1
  - Identified by a unique tag assigned by the runtime
- Every program starts with MPI_COMM_WORLD (default communicator)
  - Defined by the MPI runtime, this group includes all processes
- Several MPI routines to create sub-communicators
  - MPI_Comm_split
  - MPI_Cart_create
  - MPI_Group_incl

MPI datatypes

- Can be a pre-defined one: MPI_INT, MPI_CHAR, MPI_DOUBLE, …
- Derived or user-defined datatypes:
  - Array of elements of another datatype
  - struct datatype to accomodate sending multiple datatypes

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