Computer Engineering

Unit 3. Parallel computation

#1 TOP500 (6/2018) - Sequoia

- Manufacturer: IBM
- Cores: 1572864
- OS: Linux
- Interconnecting network: ad-hoc
- Maximum performance: 16324,8 TF
- Peak performance: 20132,7 TF
- Power: 7890 kW
- Location: Lawrence Livermore National Laboratory (LLNL)
- https://computing.llnl.gov/
- Detailed specification: https://computing.llnl.gov/?set=resources&page=OCF_resources#sequoia

#5 TOP500 (6/2018) - Tianhe 2A

- Manufacturer: NUDT (National University of Defense Technology)
- Cores: 4,981,760
- OS: Linux
- Interconnecting network: proprietary
- Maximum performance: 61,444 TF
- Peak performance: 100,678 TF
- Power: 18,482 kW
- Location: National Supercomputing Center in Guangzhou
- http://www.nscc-tj.gov.cn/en/
- Detailed specification: https://www.top500.org/site/50365

#6 TOP500 (6/2018) - Barcelona Supercomputing Center

- Manufacturer: Bull
- Núcleos: 153,216 (Xeon Platinum 8160 24C 2.1GHz)
- OS: Linux
- Interconnecting network: Intel Omni-Path
- Maximum performance: 6,470,2 TF
- Peak performance: 10,297 TF
- Power: 1,632 kW
- Location: Barcelona Supercomputing Center
- http://www.bsc.es/
- Detailed specification: https://www.bsc.es/discover-bsc/the-centre/marenostrum

Where is used supercomputation?

- Defense
  - Terrorism
  - Weapons program
  - Spatial program
- Engineering/Academic/Research
  - New energies prospection and simulation
  - Nanotechnology
  - Biological modeling
  - Deep learning
  - Genome research
  - Protein research
  - Astrophysical simulations
  - Weather forecasting
  - Drug design
  - Geological modeling
  - ...

Concepts and motivation

Parallel processing versus distributed processing:

Parallel processing:

○ How and when to split an application into independent computing units to **speed-up** the execution? How are these units executed and how the application can be scalable in terms of complexity and performance?

Distributed processing:

○ How to execute at the same time diverse applications using the same resources → distribution of time and resources (processor, memories, disks...)

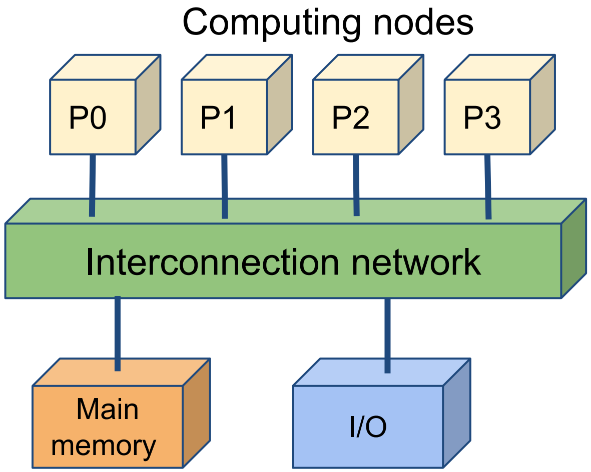
Concepts and motivation

Parallel computer classification (regarding their memory system)

- **Multiprocessor**: Nodes sharing the same addressing space (programmers needn't know where data are locate)
- **Multicomputer:** Each node has its own addressing space (programmers problem → in which node are my data)

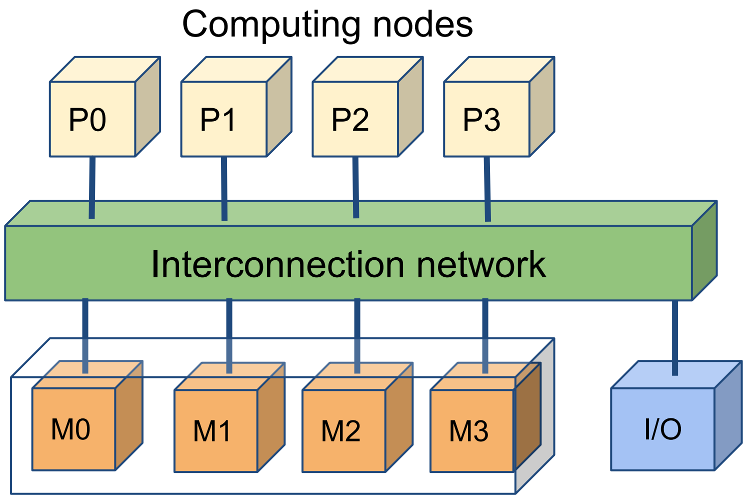
Parts of a parallel computer:

- Computing nodes
- Memory system
- Communication system
- Input/Output system

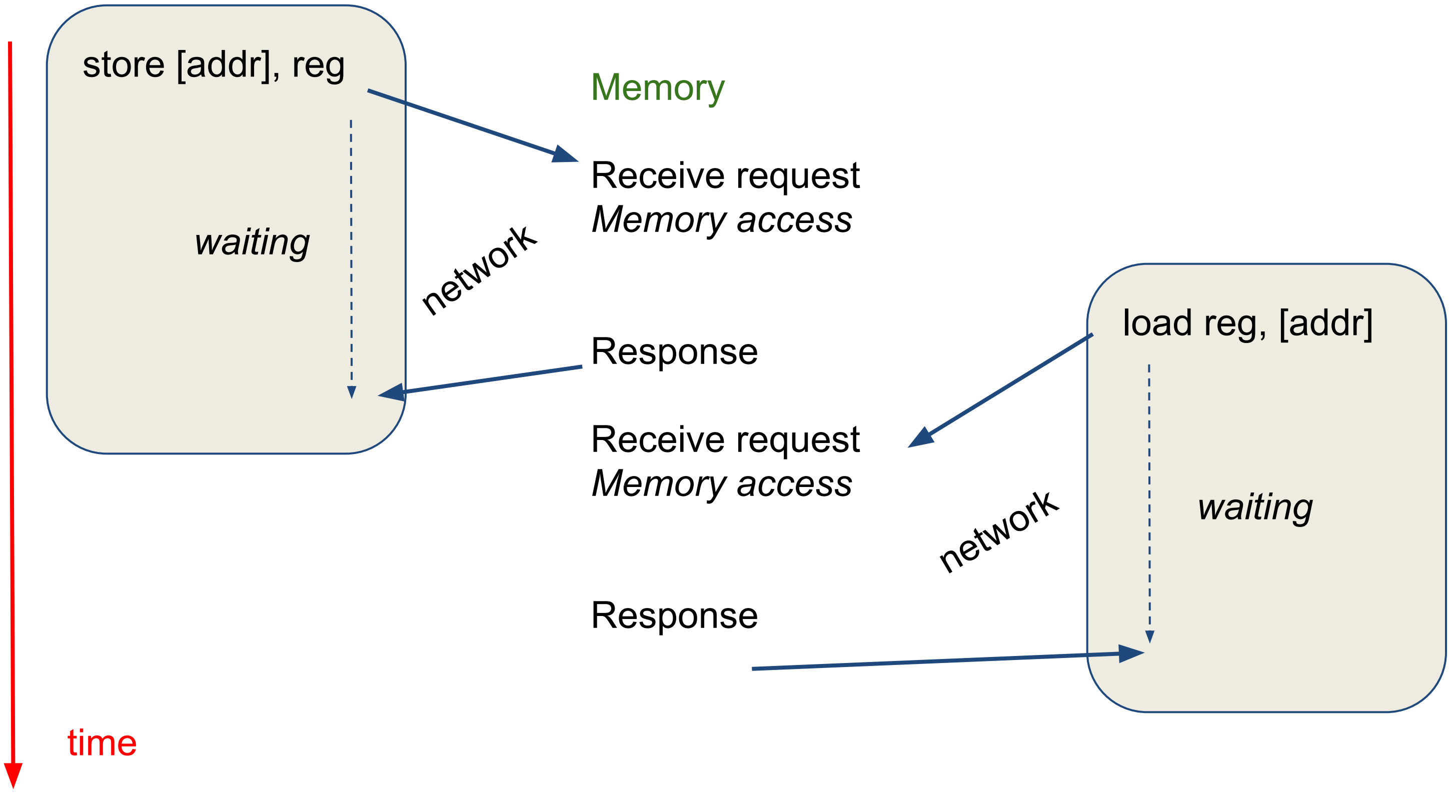


Multiprocessors: NUMA & SMP/UMA (Symmetric Shared Memory or Uniform Memory Access Multiprocessors

- ○ Higher latency
- ○ Less scalable → Why?
- ○ Communication by shared variables (no data replication)
- ○ Synchronization primitives are needed.
- ○ No need to distribute code and data → Why?
- ○ Programming is usually friendly



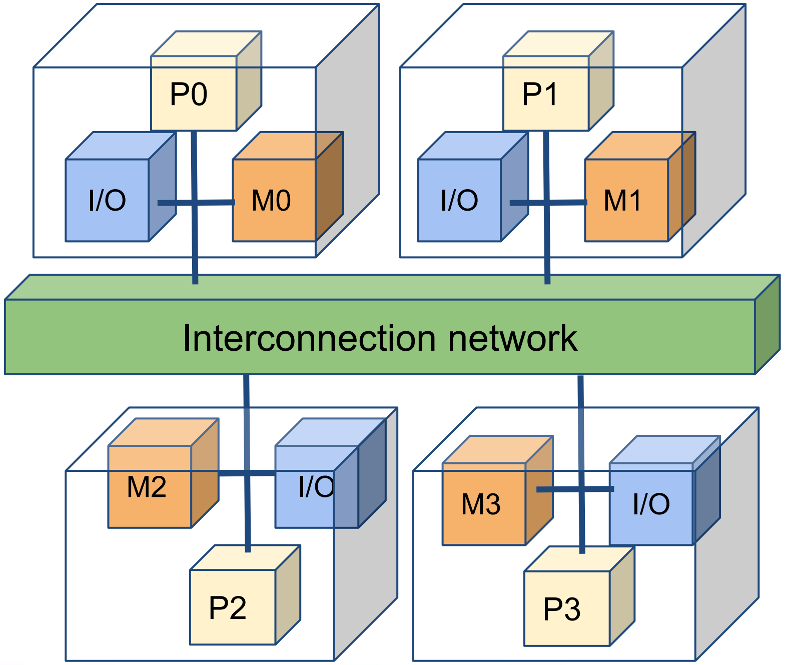
Communication in a multiprocessor



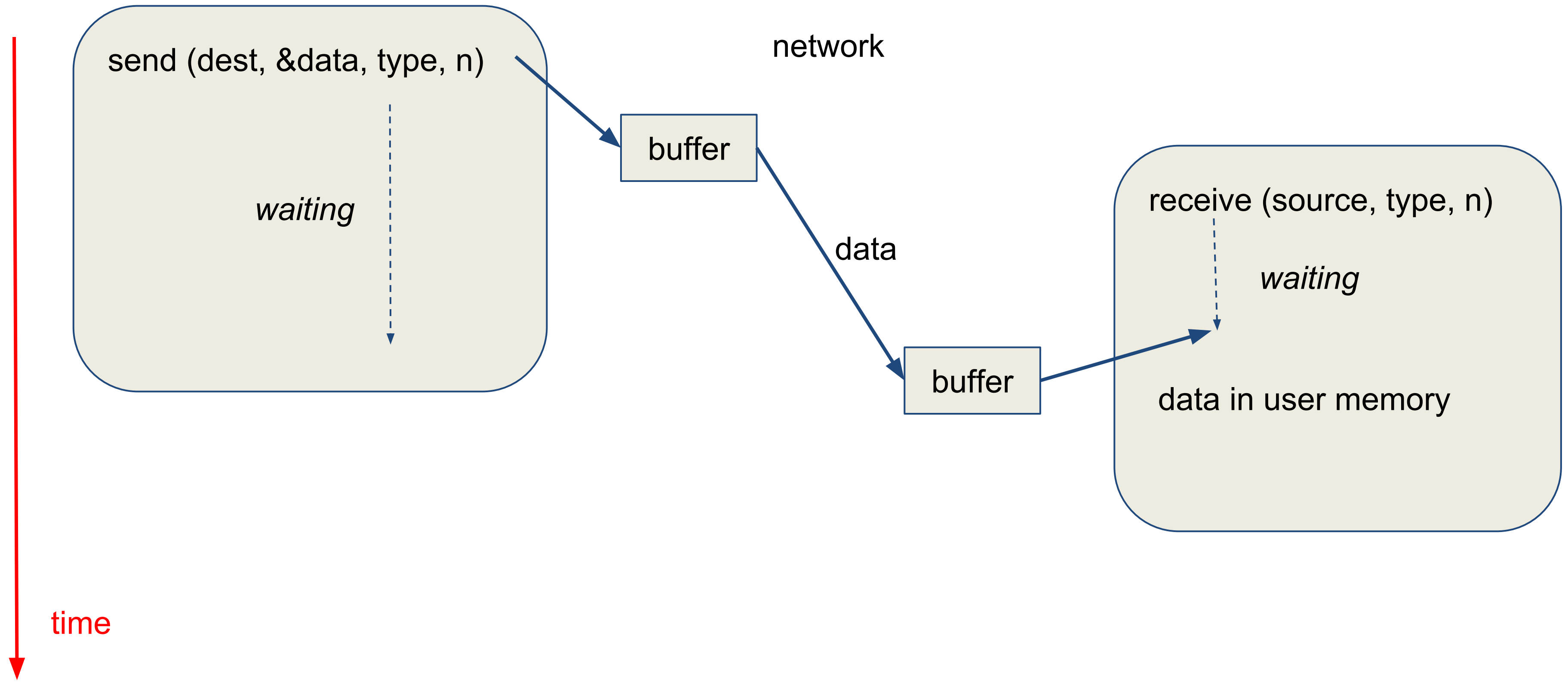
Concepts and motivation

Multicomputer

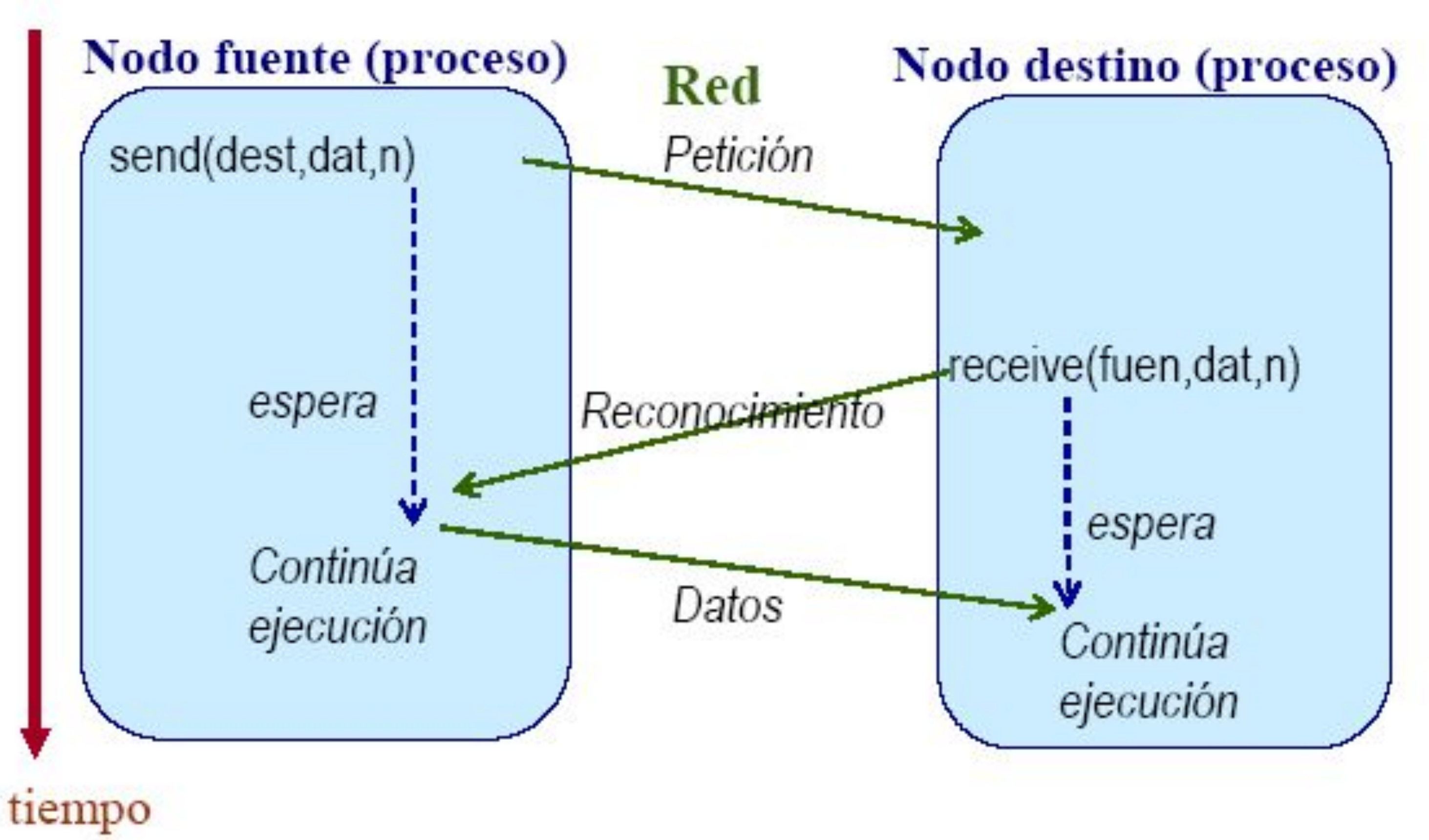
- ○ Lower latency
- ○ Higher scalability
- ○ Communication by message passing (duplicated data)
- ○ Synchronization by means of communication mechanisms
- ○ Workload (code and data) is distributed among processors
- ○ Programming is a bit more complicated



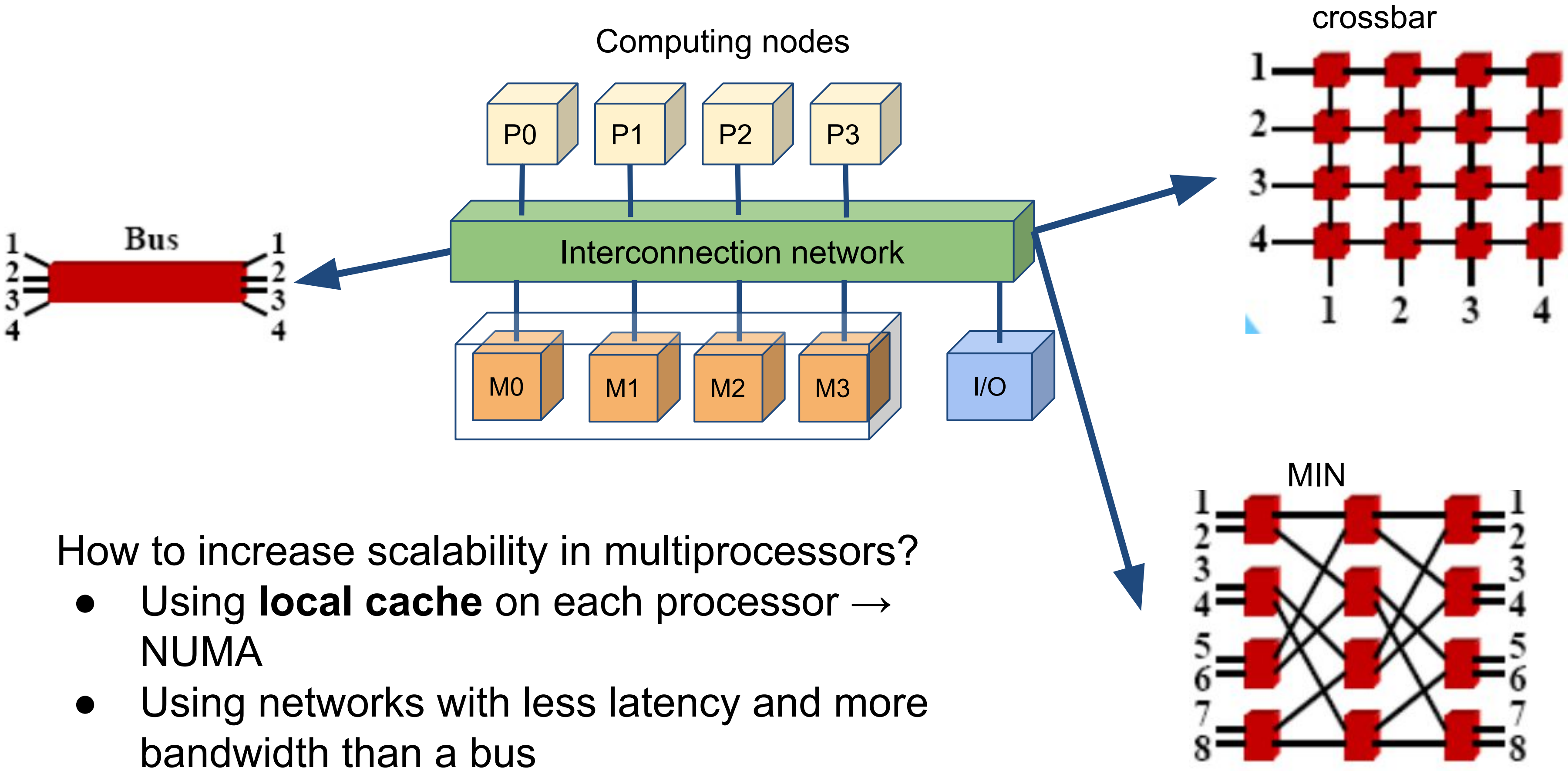
Asynchronous communication in a multicomputer



Synchronous communication in a multicomputer



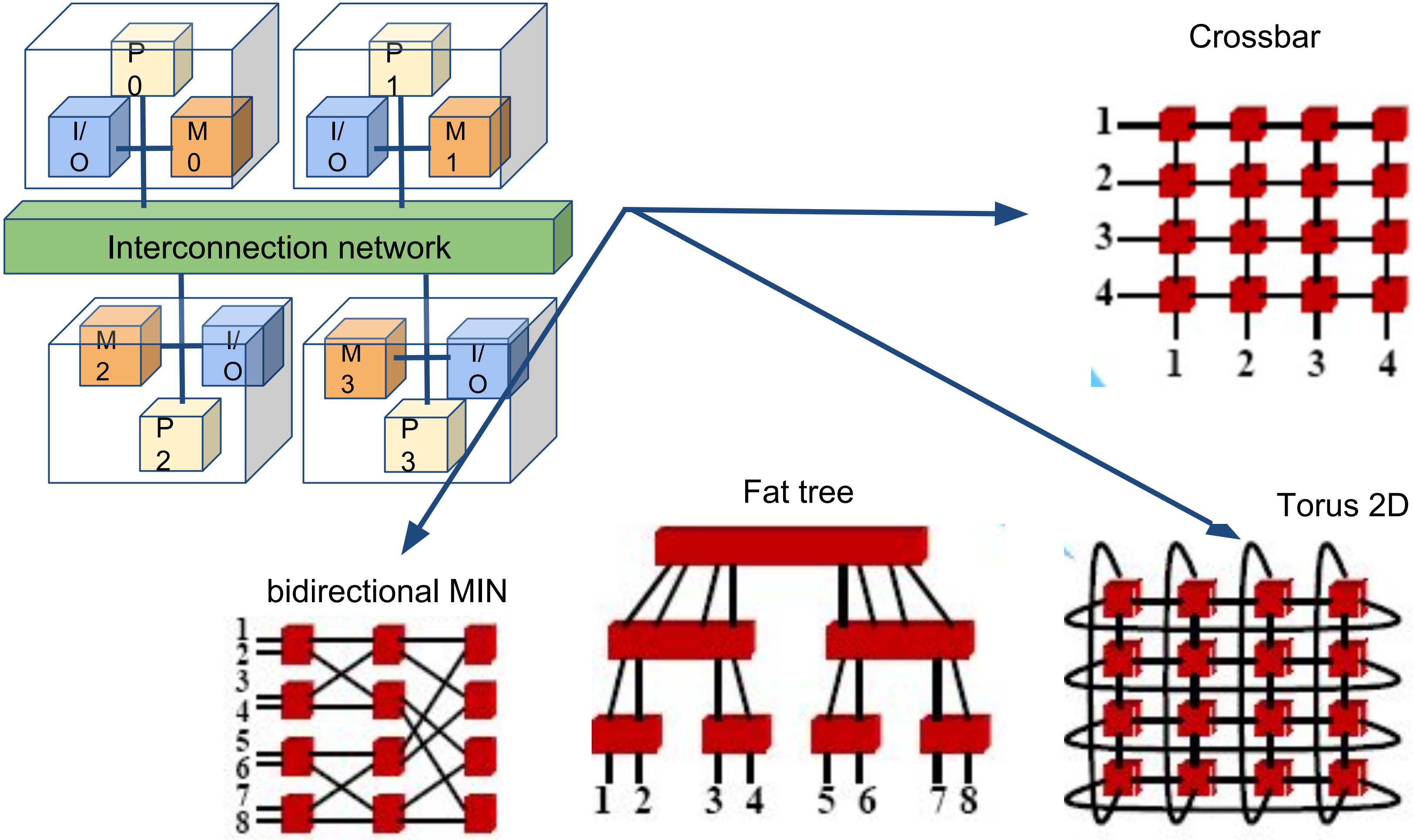
Interconnecting networks in multiprocessors



How to increase scalability in multiprocessors?

- Using **local cache** on each processor → NUMA
- Using networks with less latency and more bandwidth than a bus
- Turn UMA into NUMA

Interconnecting networks in multiprocessors



Parallel computer and scalability

We can sort the parallel computer in terms of their increasing scalability:

UMA/SMP < COMA < CC-NUMA < NUMA < Multicomputers

Examples:

Multicomputers:	IBM-SP2, HP AlphaServer SC45 (cluster o SMP)
NUMA :	Cray T3E, Cray X1
CC-NUMA :	Origin 3000, HP 9000 Superdome
COMA:	KSR-1
SMP:	Try to guess

Other parallel computers:

- **MPP (Massive Parallel Processor)**: # of processors > 200. These systems have ad-hoc networks.
- **Cluster**: A set of
- A computer cluster is a set of connected computers that work together. They can be viewed as a single computer resource. The traffic is reduce to that caused by the application.
- **Cluster Beowulf**: Cluster using (Linux) and common hardware and software
- **Constellations**: Large-scale multiprocessors that use clustering of smaller-scale multiprocessors, typically with a DSM or SMP architecture and 32 or more processors.

Other parallel computers:

- **Network of computers**: Set of computer connected using a LAN.
- **GRID**: A computer made of widely distributed computer resources to reach a common goal.

Types of parallelism

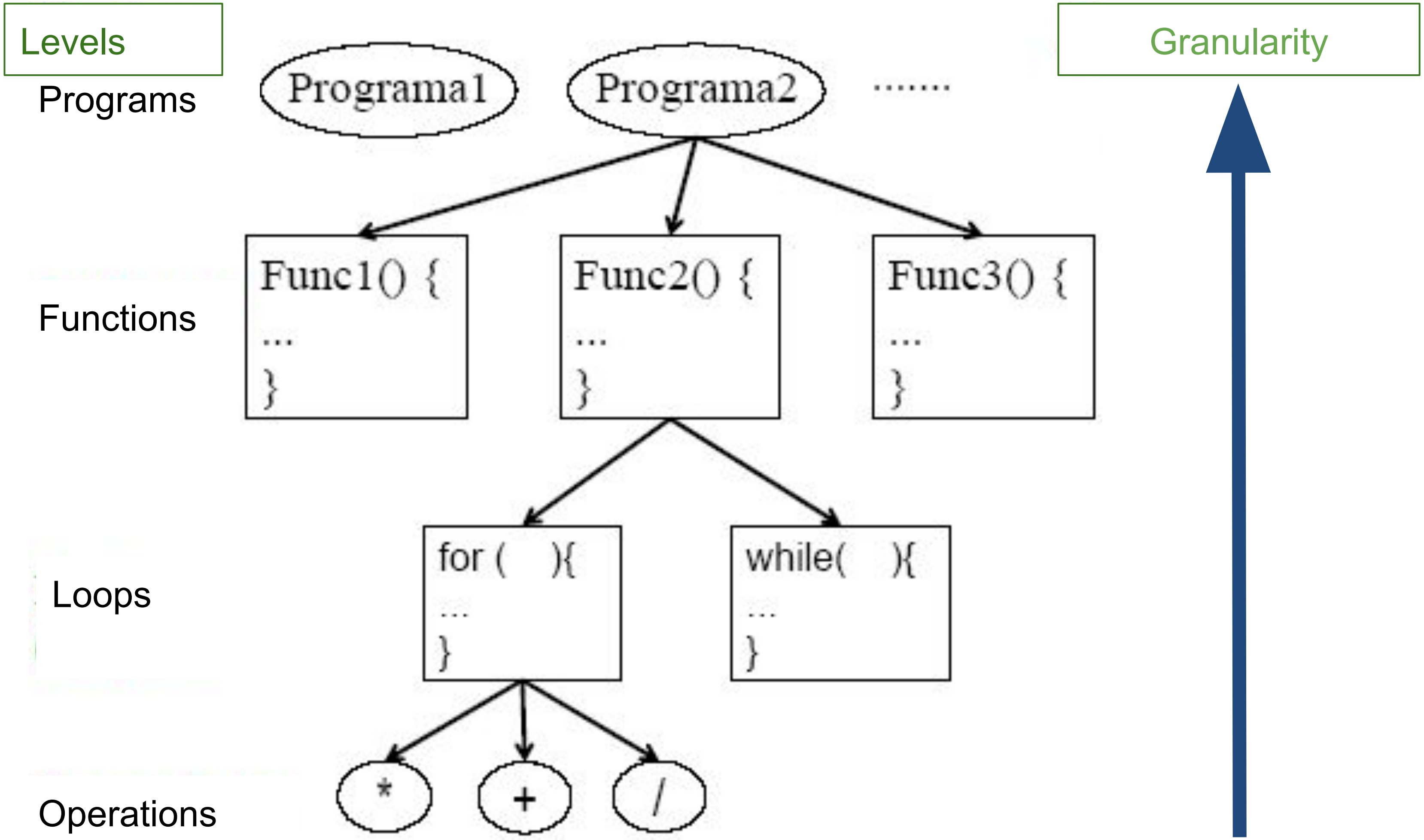
Functional parallelism

○ Obtained from a reorganization of the logic structure of an application. Different levels based in the different software structures (software blocks) taken into account (basic blocks, loops, functions, set of functions, …). How many software blocks can I run in parallel?

Data parallelism

○ Implicit when operating with structures such as vectors or matrices. Related with operations over a big amount of independent data.

Functional parallelism



Types of parallelism regarding its visibility

Explicit parallelism

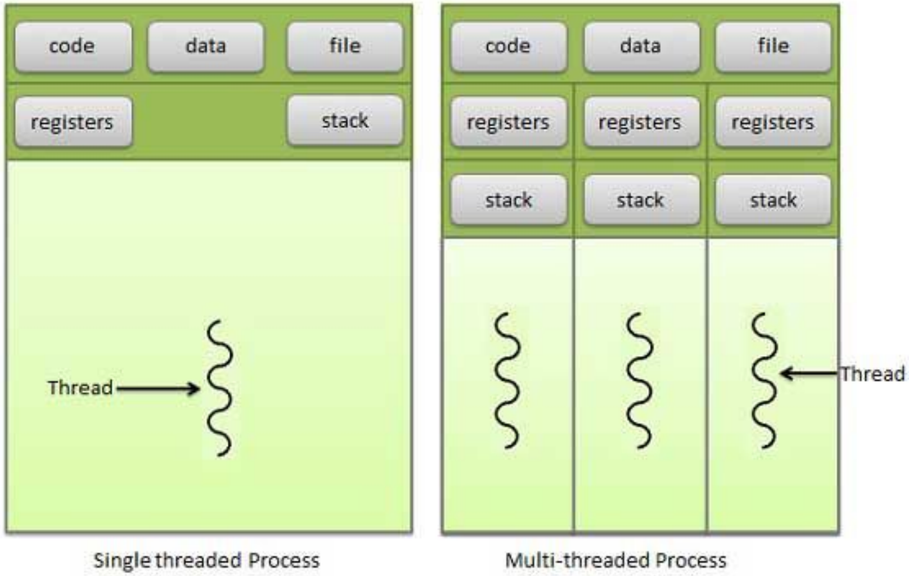
- If we must express parallelism because it is not present in the language common structure. (I.e. MPI application)

Implicit parallelism

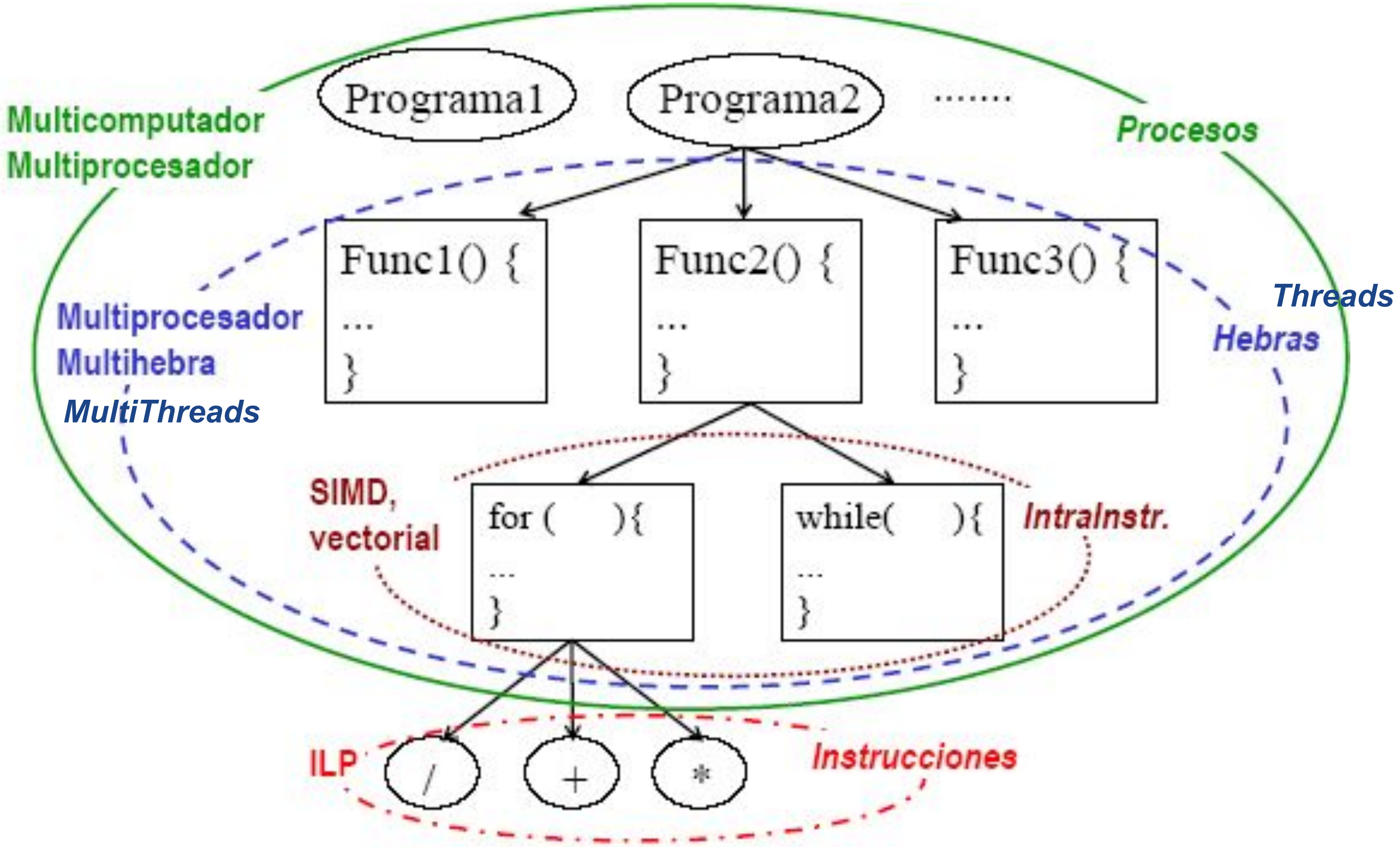
- If we have language structures (loops, vectors, matrices) that naturally can express parallelism (although it can be unexploited).

Execution units for parallelism: threads and processes

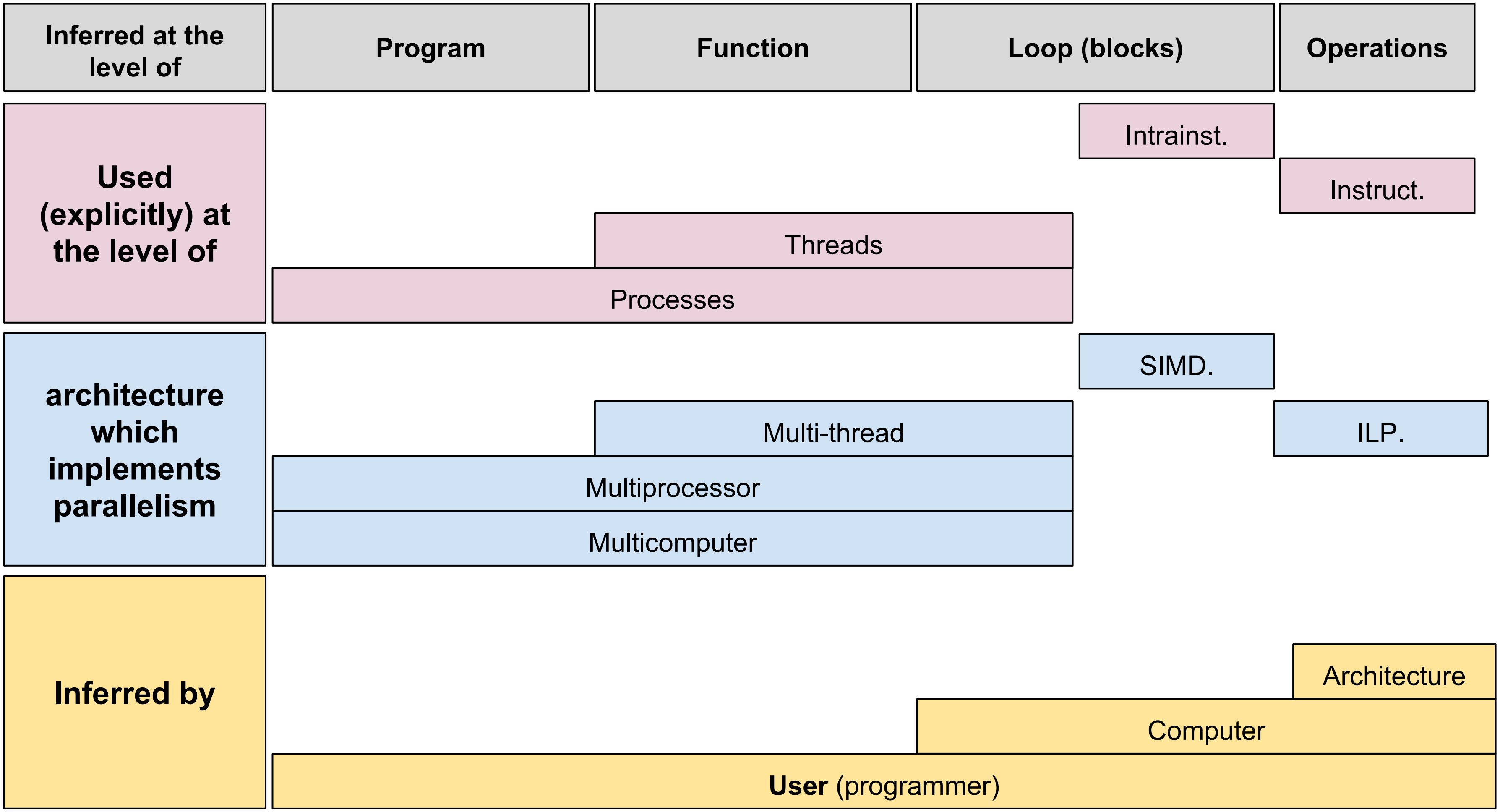
- Hardware (processor): Manage the execution of instructions.
- Software (O.S.). Manage the execution of threads and processes.
  - **Processes**: Have their own virtual addressing space.
  - **Threads**: share virtual addresses, but can be created and destroyed faster than processed and also, the communication is faster.



Concepts and motivation



Parallelism detection and extraction



Inferred at the level of

Program

Function

Loop (blocks)

Operations

Used (explicitly) at the level of

Intrainst.

Instruct.

Threads

Processes

architecture which implements parallelism

SIMD.

Multi-thread

ILP.

Multiprocessor

Multicomputer

Inferred by

Architecture

Computer

User (programmer)

Parallel programming tasks/challenges:

- ○ Code splitting into independent computing units (tasks)
- ○ Task grouping (code & data) into processed/threads
- ○ Computing units (cores) assignment
- ○ Synchronization & Communication

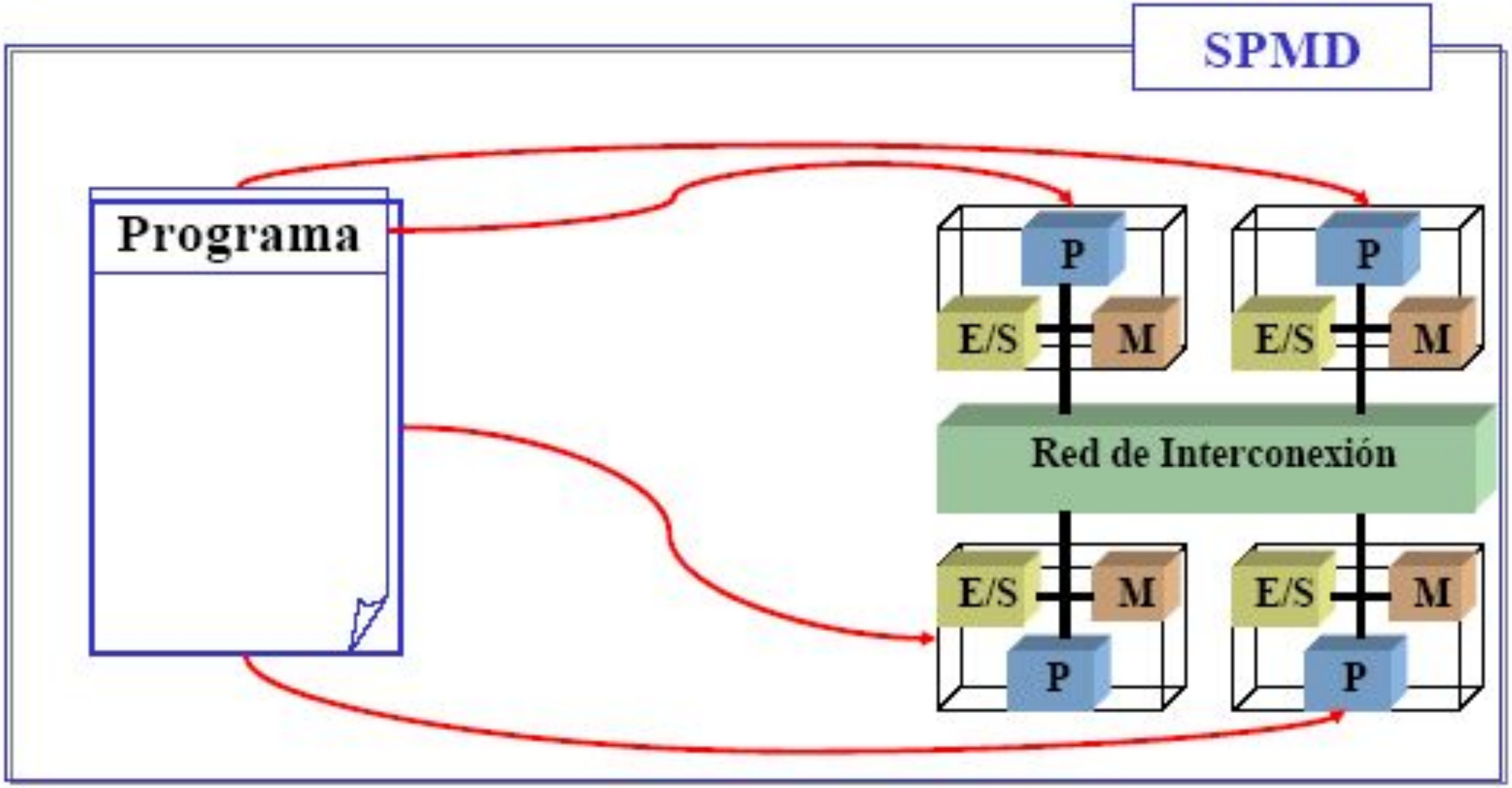
Usual starting point

- ○ Sequential version of the code to be parallelized
- ○ Functional description of the code
- ○ Supporting elements:
  - ■ Parallel code resolving similar problem
  - ■ Parallel libraries (BLAS, ScalaPACK, OpenMP, Intel TBB, ...)

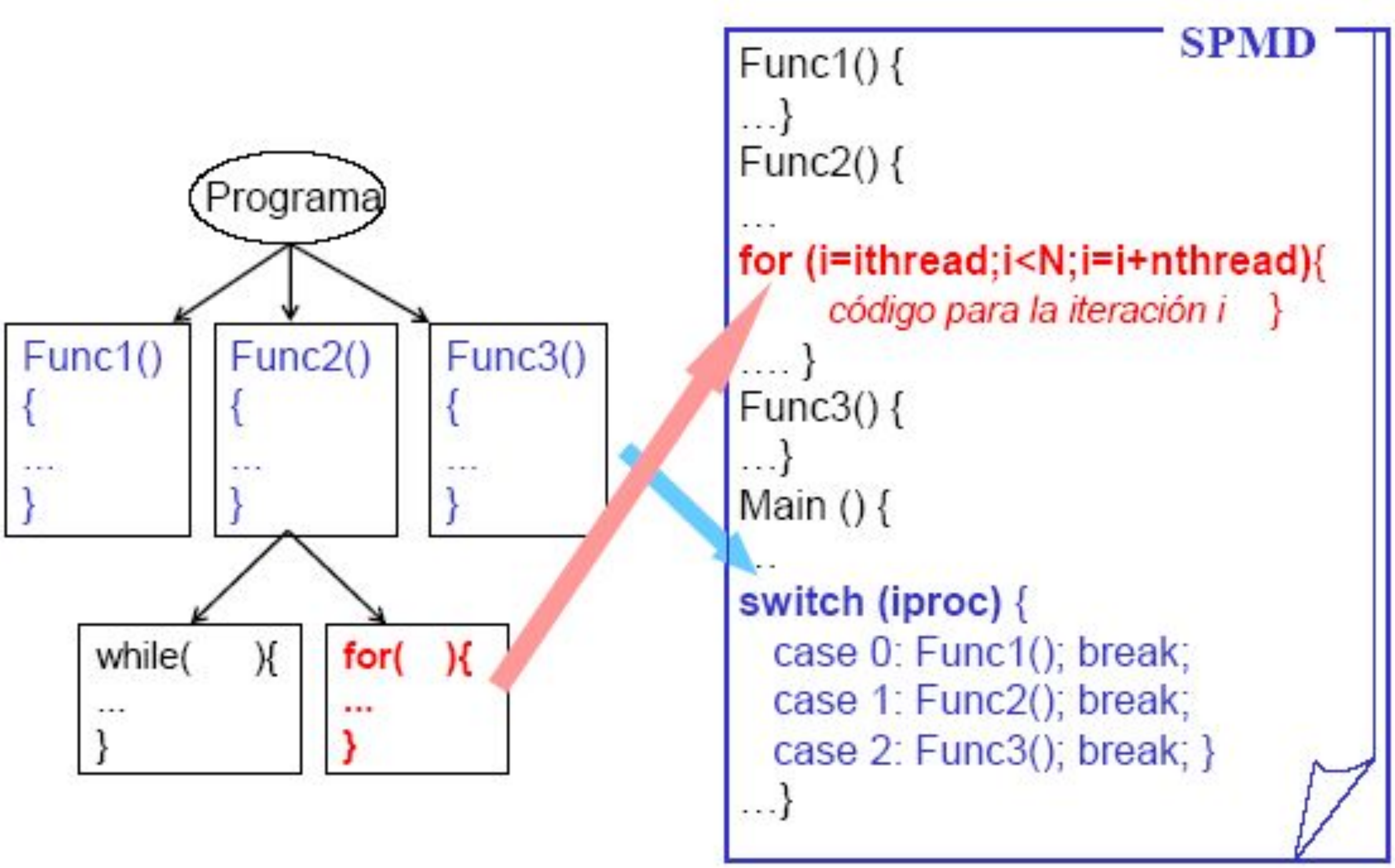
Techniques and procedures

Parallel programming modes:

- **SPMD** (Single Program Multiple Data)



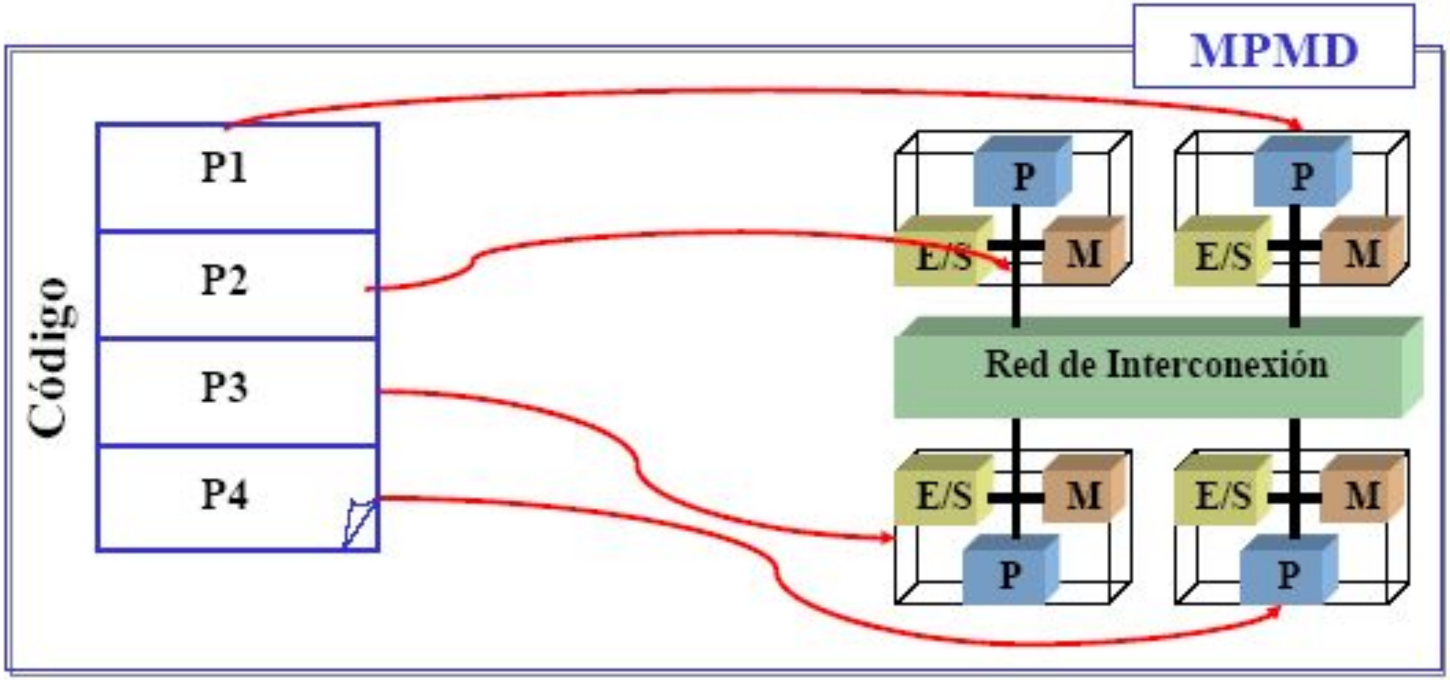
SPMD Example



```
Func1() {
…}
Func2() {
…
for (i=ithread;i<N;i=i+nthread){
      código para la iteración i    }
…. }
Func3() {
…}
Main () {
…
switch (iproc) {
  case 0: Func1(); break;
  case 1: Func2(); break;
  case 2: Func3(); break; }
…}
```

Parallel programming modes:

- **MPMD** (Multiple Program Multiple Data)



- **Hybrid SPMD-MPMD**

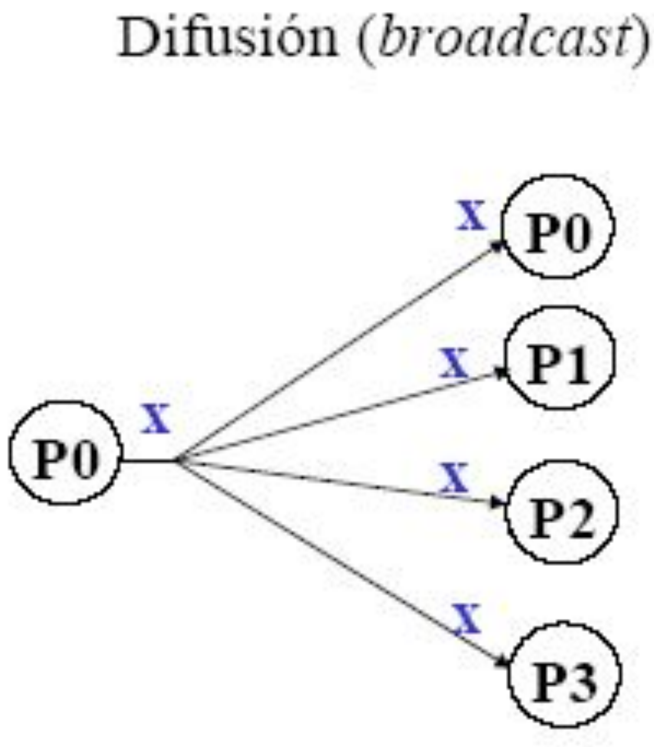
Tools supporting parallel programming

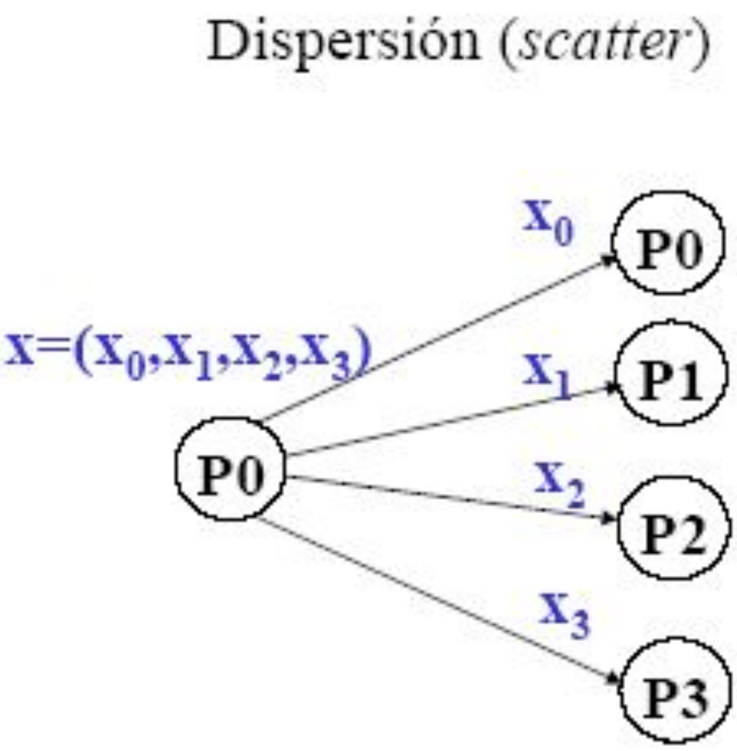
- Parallel compiler. Automatic inference of parallelism.
- Compiler directives/pragmas/artifacts (OpenMP)
- Parallel languages (HPF, Occam, Ada)
- Libraries: PThreads, MPI, PVM, Intel TBB (sequential code + interfacing functions)

Collective communication

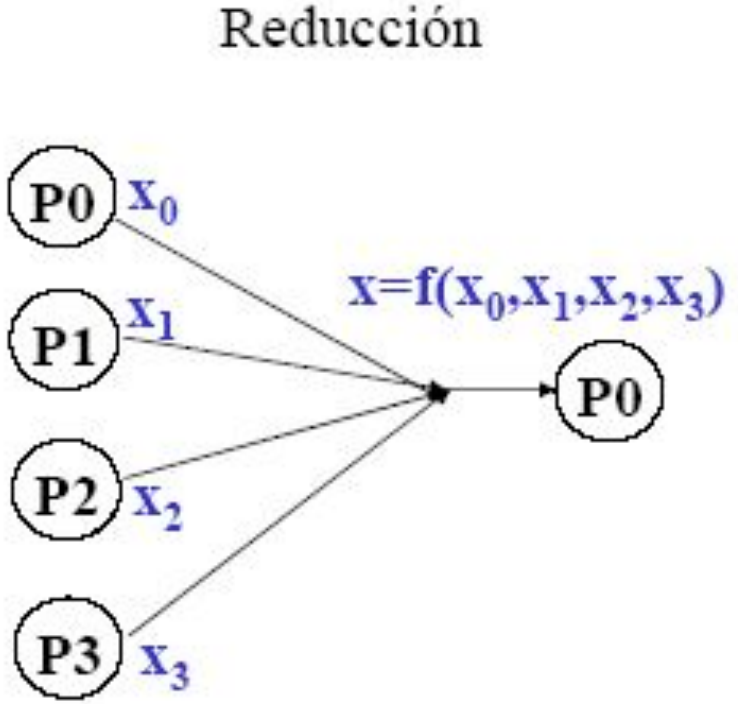
- **One to all** : broadcasting (MPI_Bcast), scattering (MPI_Scatter)
- **All to one**: Reduction (MPI_Reduce), gathering (MPI_Gather)
- **All to all complete exchange**: All-broadcast (MPI_AllBroadcast), All-scattering (MPI_AllScatter)
- **Multiple one-by-one**: Permutations, Shifting
- **Composed services**: barrier synchronization (MPI_Barrier), scan (MPI_Scan)

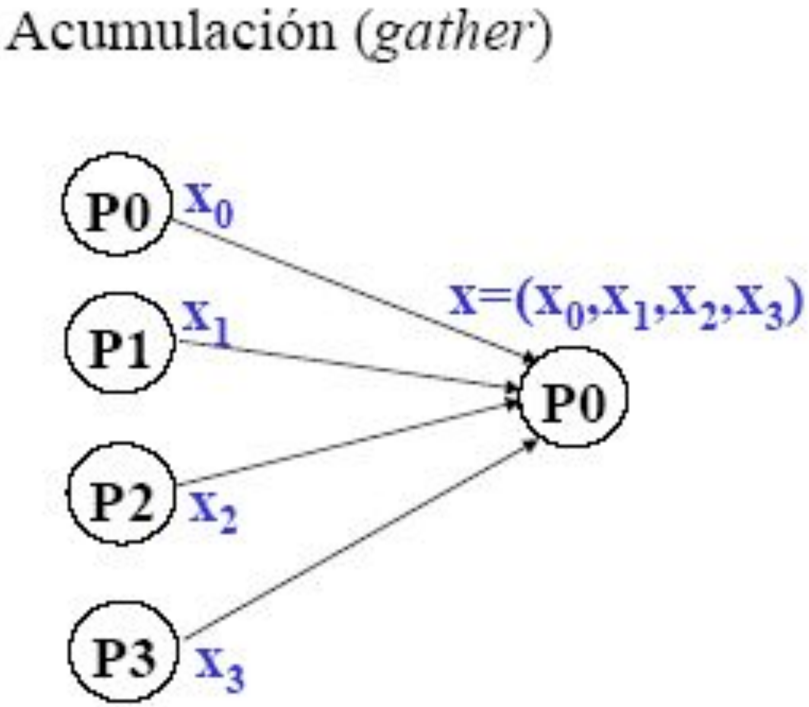
Collective communication: **one by all**



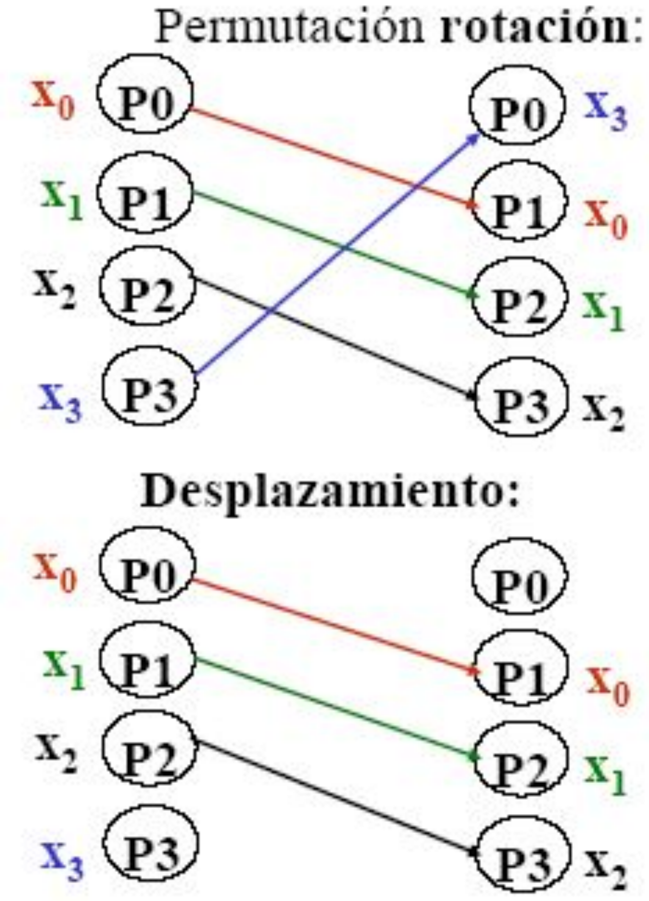


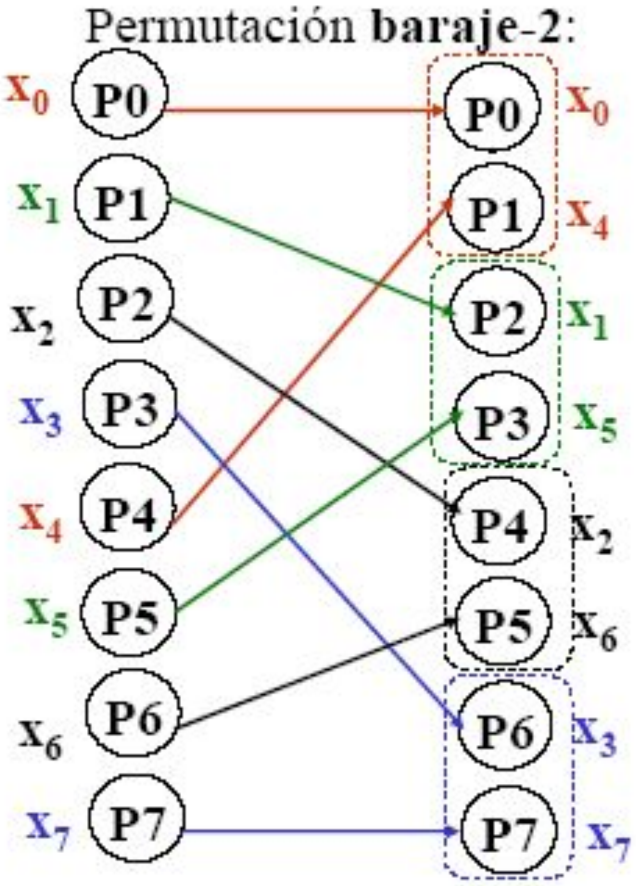
Collective communication: **all to one**



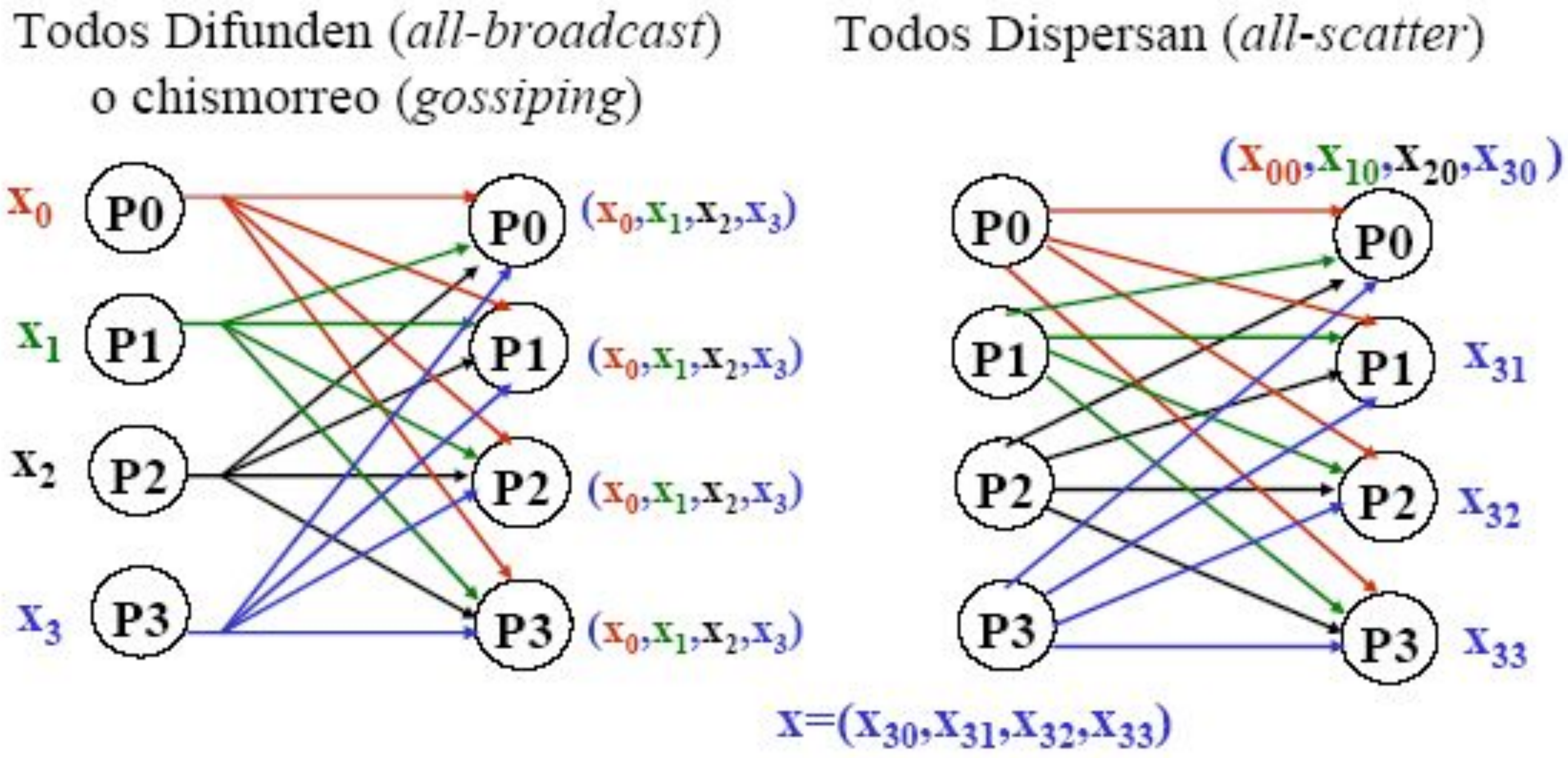


Collective communication: **multiple one-by-one**





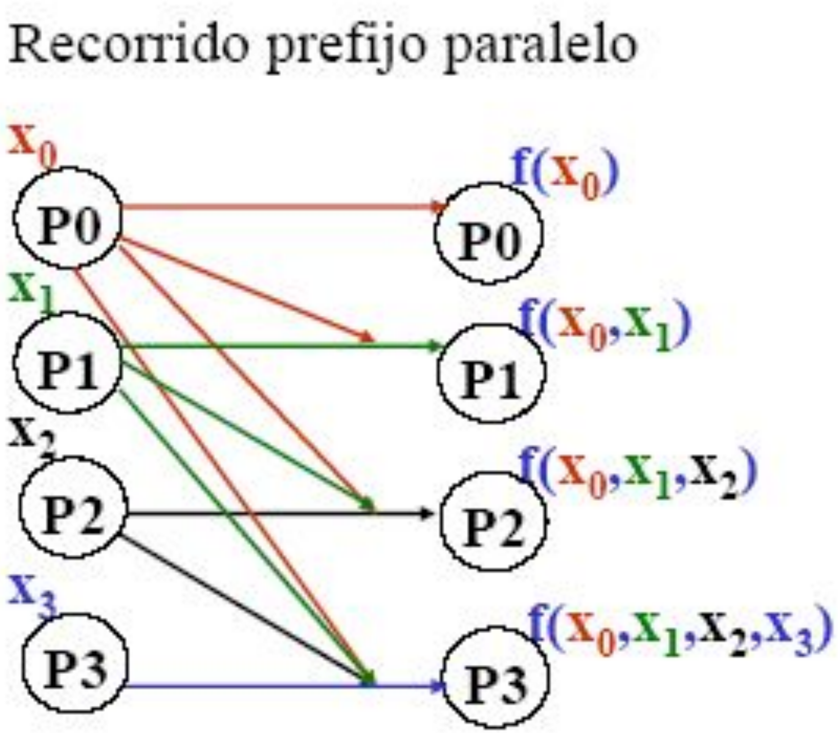
Collective communication: **all to all**

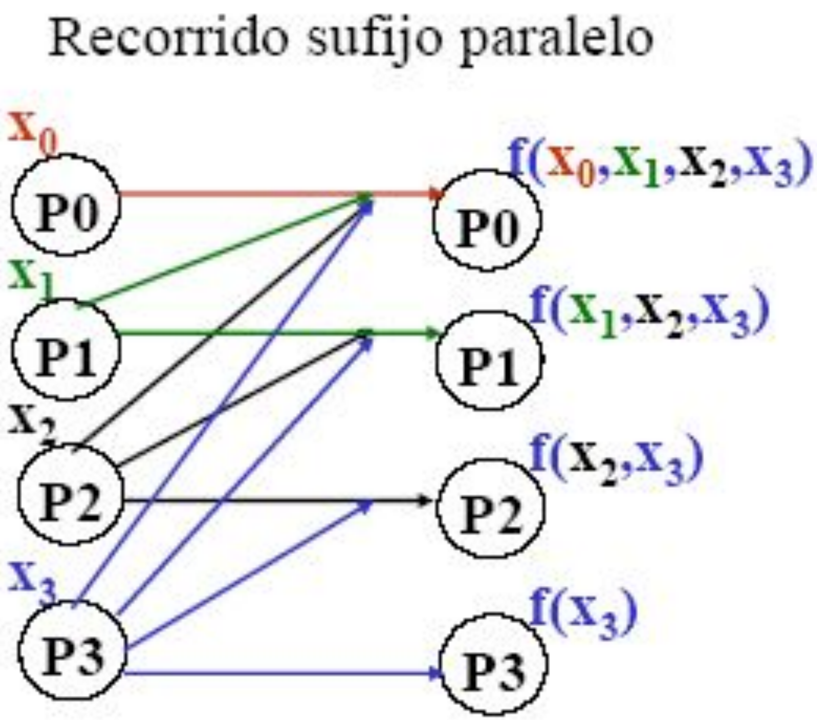


Todos Difunden (*all-broadcast*) o chismorreo (*gossiping*)

Todos Dispersan (*all-scatter*)

Collective communication: **compound services**





Parallel programming styles: **message passing**

- Software tools:
  - Programming languages (Ada2012) and libraries (MPI, PVM, Intel TBB)
- Workload distribution:
  - Using libraries: explicitly with language sequential sentences (if, for, ...)
  - Using a parallel language: explicitly with language special primitives (I.e. Occam’par)
- Basic communicating primitives : Send and Receive
- Collective communication functions
- Synchronization
  - Blocking receive. Barriers (I.e. MPI_Barrier)
  - Blocking Send-receive (I.e ADA)

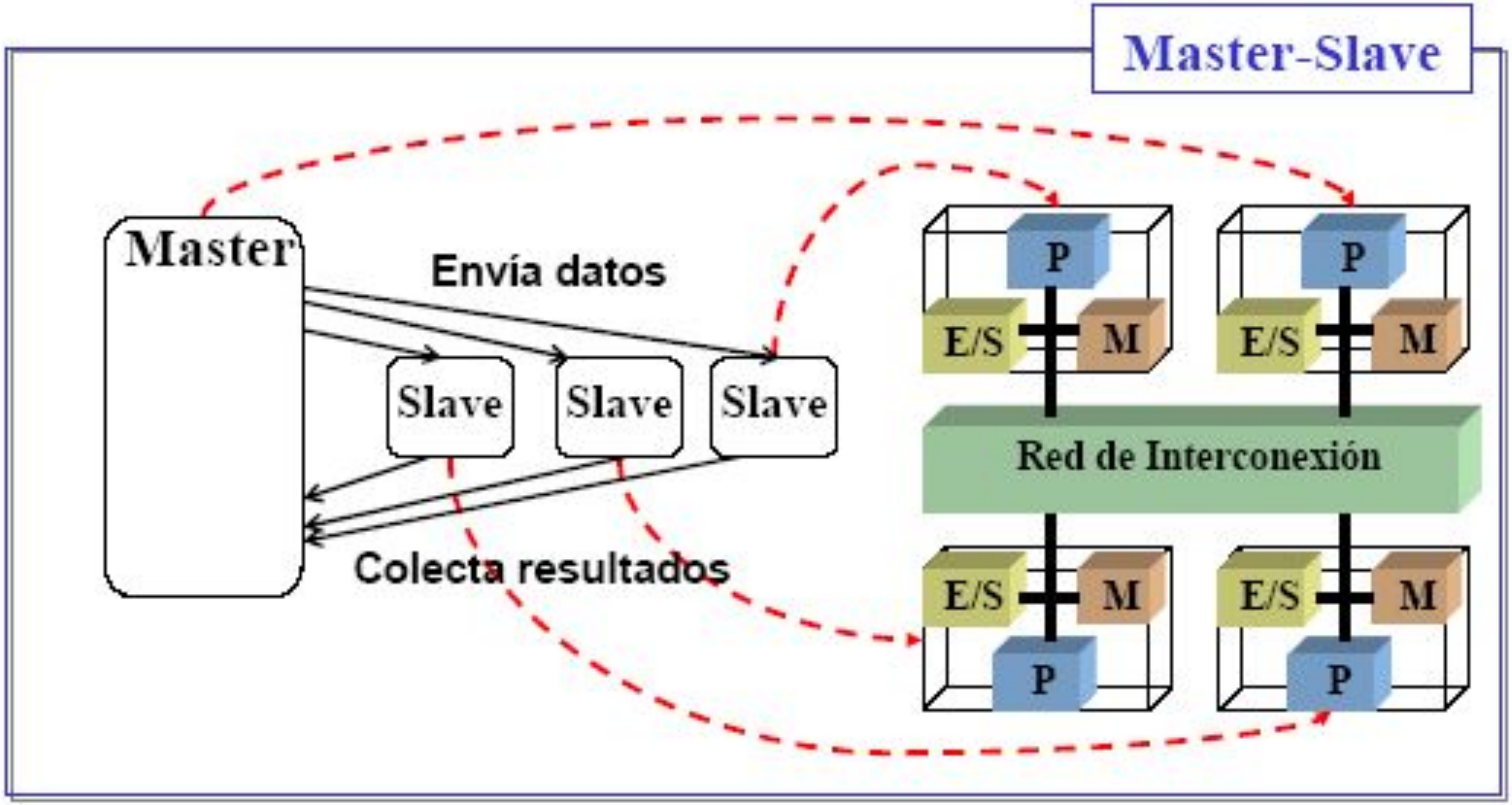
Parallel programming styles: **shared variables**

- Programming languages (Ada), libraries (OpenMP, Intel TBB), compiler directives+functions (OpenMP)
- Workload distribution
  - Libraries: explicit within the sequential code
  - Directives: implicit synchronization (higher abstraction level)
  - Languages: built-in language constructions
- Basic communication: load & store
- Collective communication
- Synchronization
  - Semaphores, conditional variables, locks

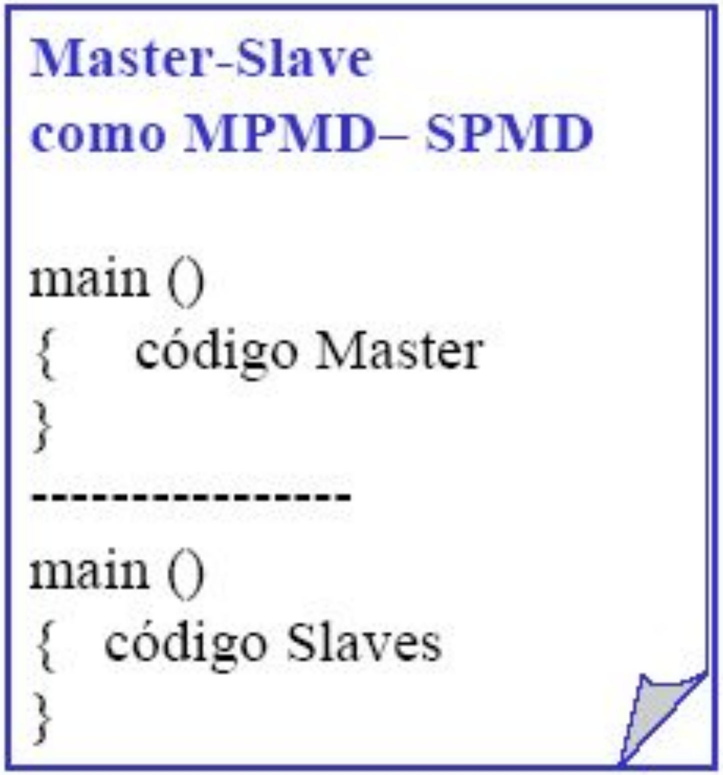
Parallel programming styles: **data parallelism**

- Tools
  - Programming languages (HPF – High Performance Fortran)
- Workload distribution
  - Directives to distribute data among processors
  - Directives for loop parallelization
- Basic communication: implicit → `A(i)=A(i-1)`
- Collective communication
  - Implicit in the functions used by the programmer (I.e. rotations – CSHIFT)
- Synchronization: implicit

Parallelism structures: **master-slave**

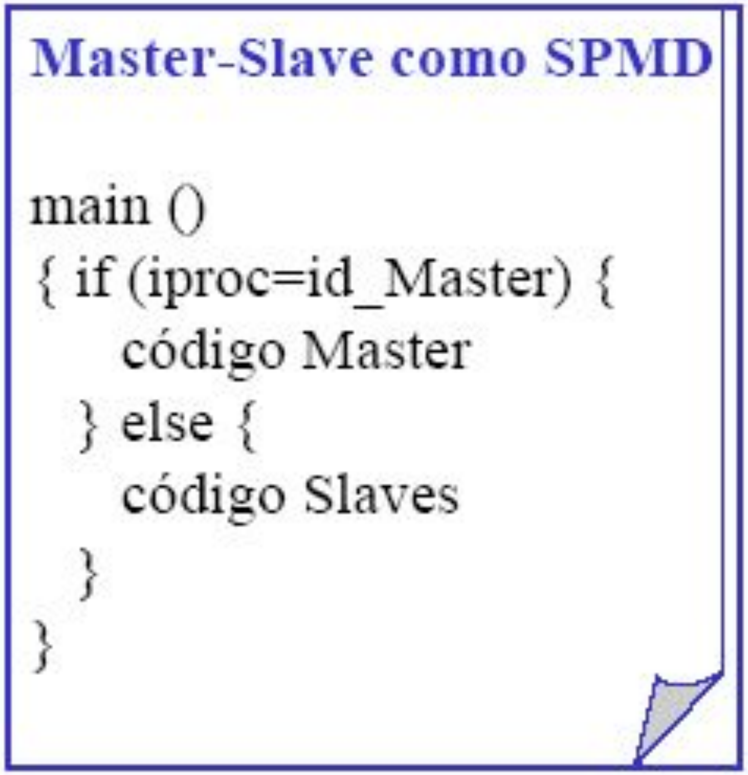


Parallelism structures: master slave (using 2 different parallel modes)



Master-Slave como MPMD– SPMD

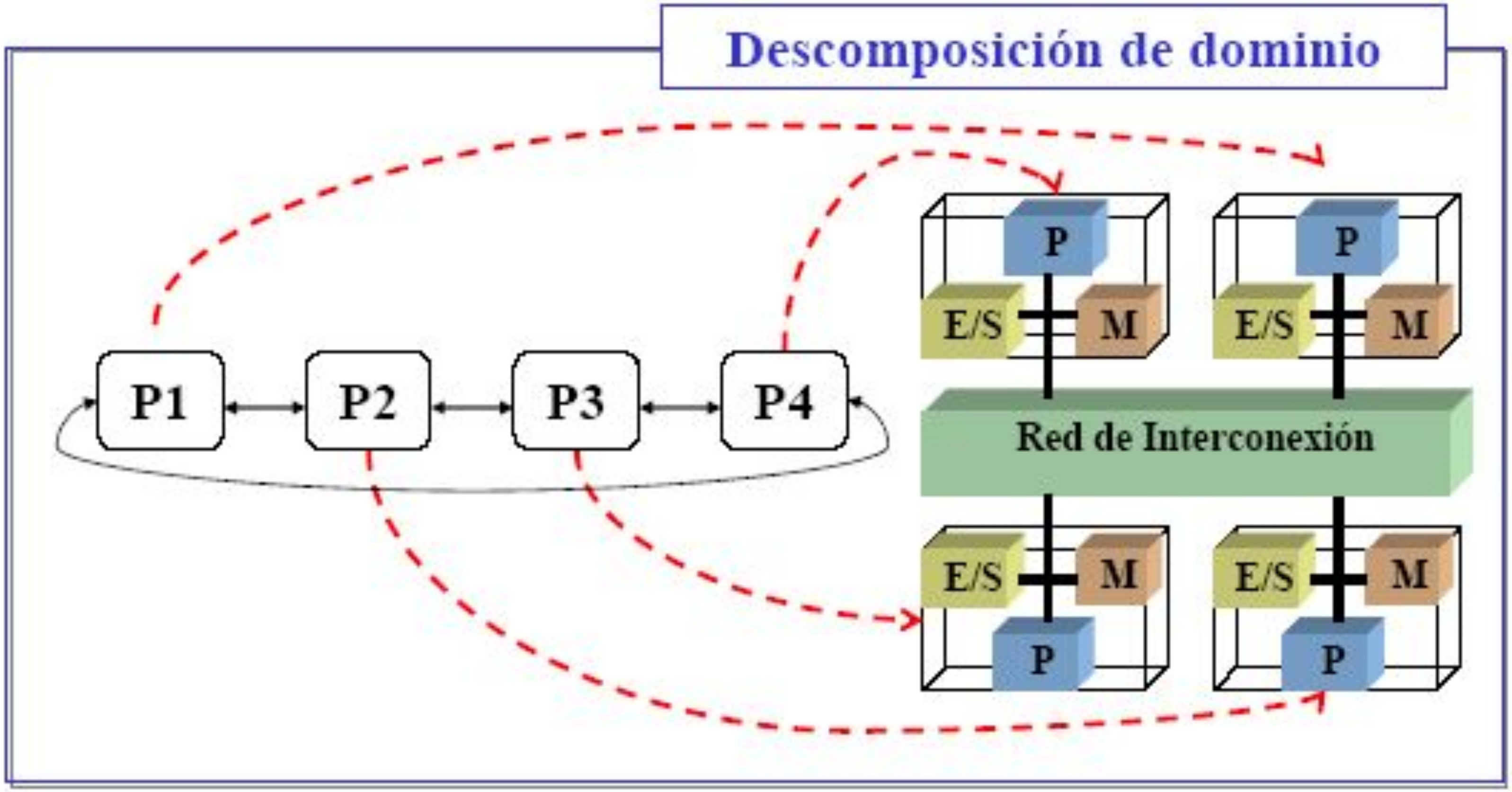
```
main ()
{    código Master
}
----------------
main ()
{   código Slaves
}
```



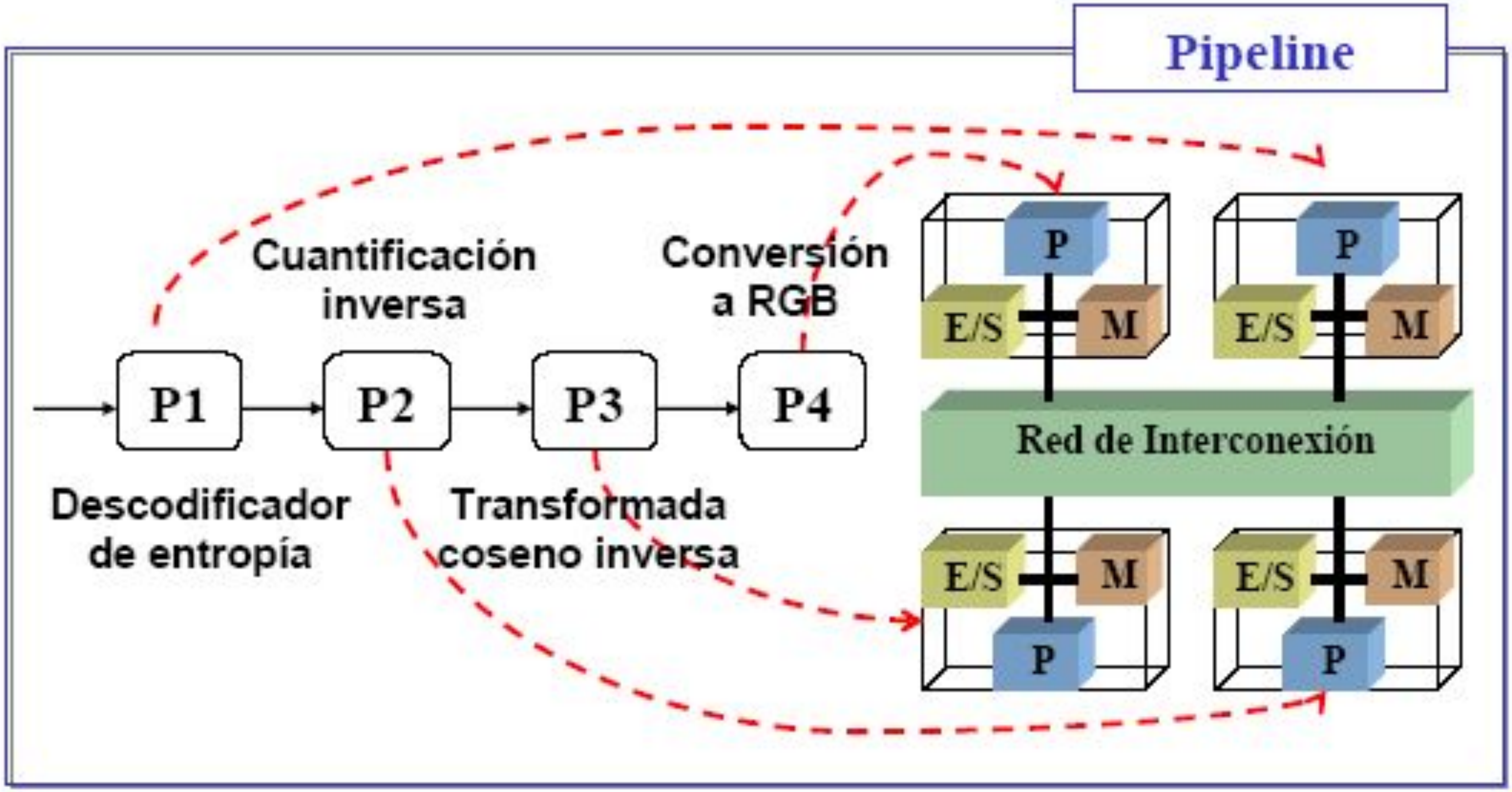
Master-Slave como SPMD

```
main ()
{ if (iproc=id_Master) {
      código Master
  } else {
      código Slaves
  }
}
```

Parallelism structures: **domain decomposition → data parallelism**

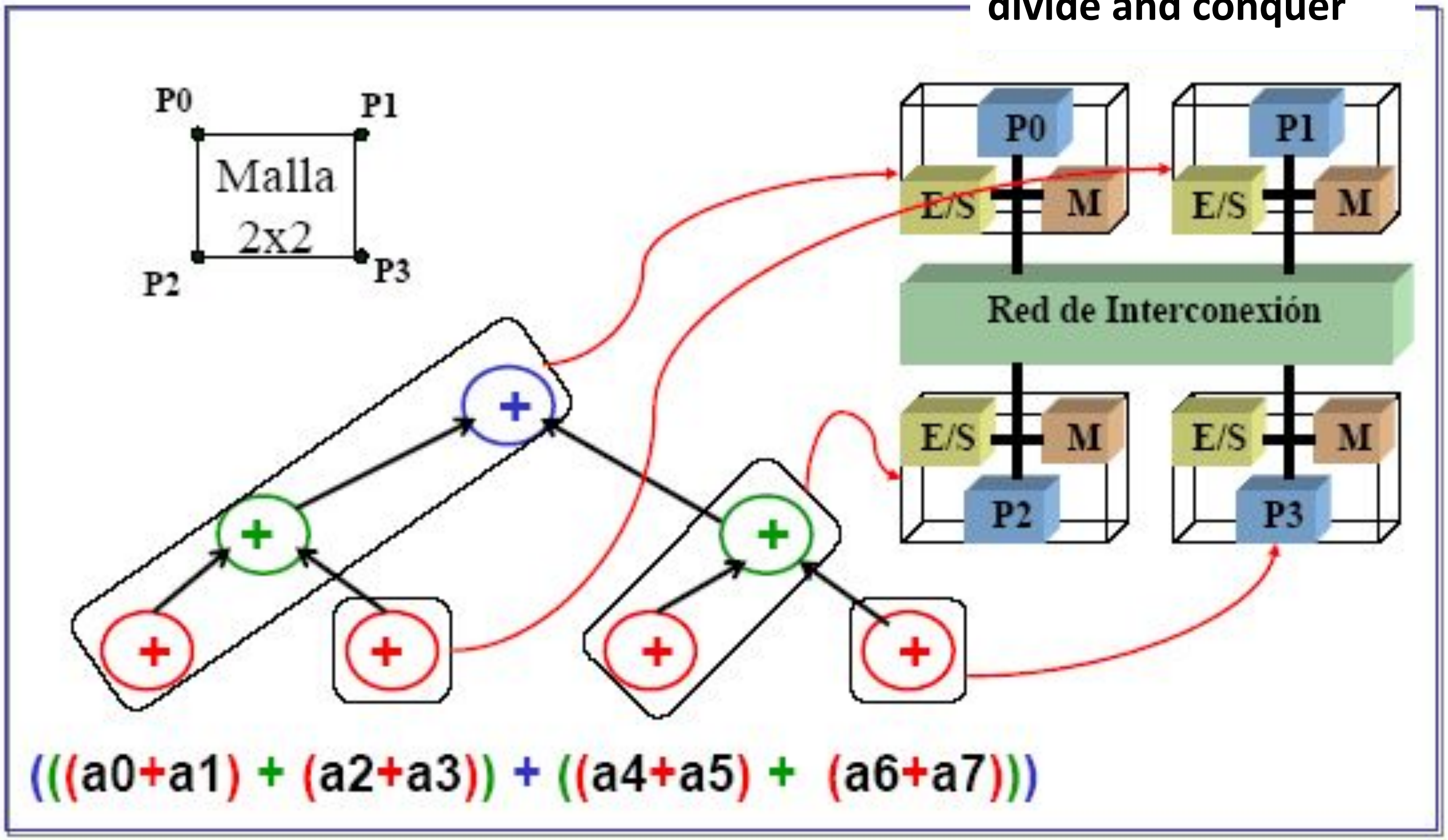


Parallelism structures: pipeline → data flow



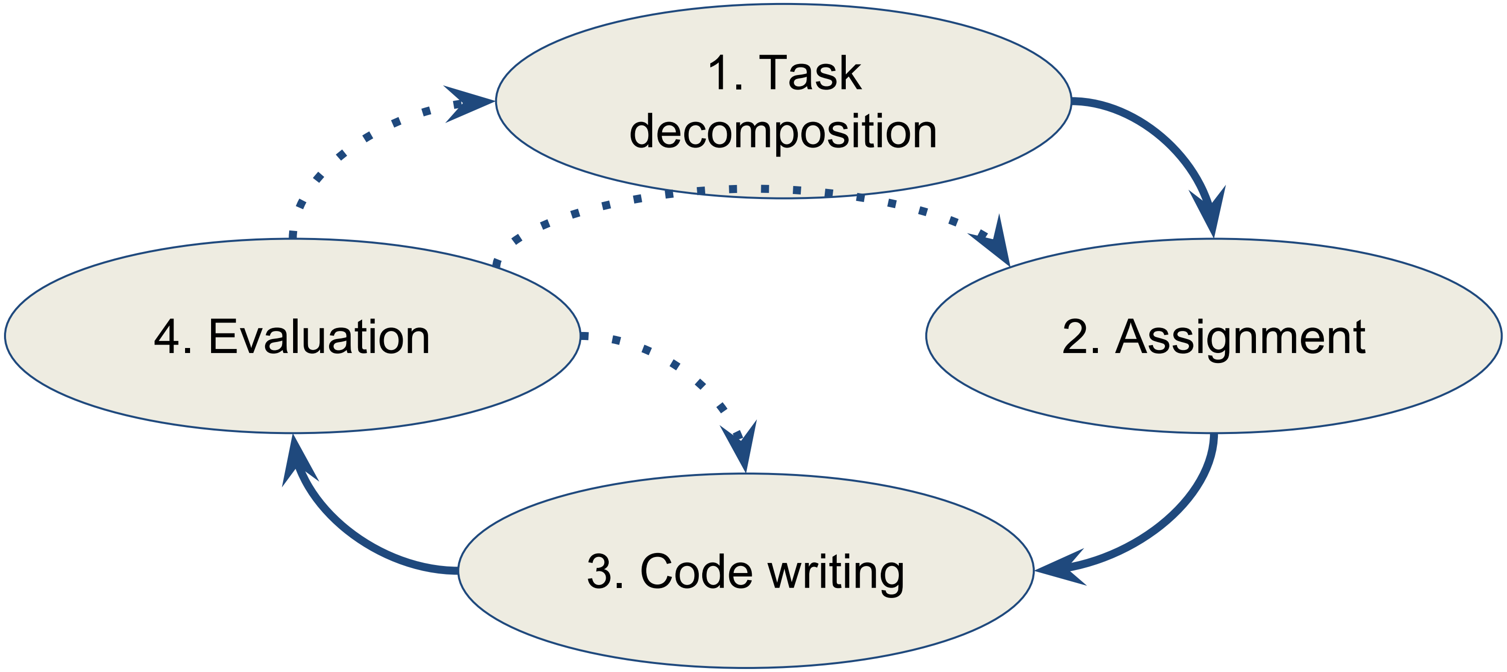
Parallelism structures: **divide and conquer** (recursive decomposition)

divide and conquer



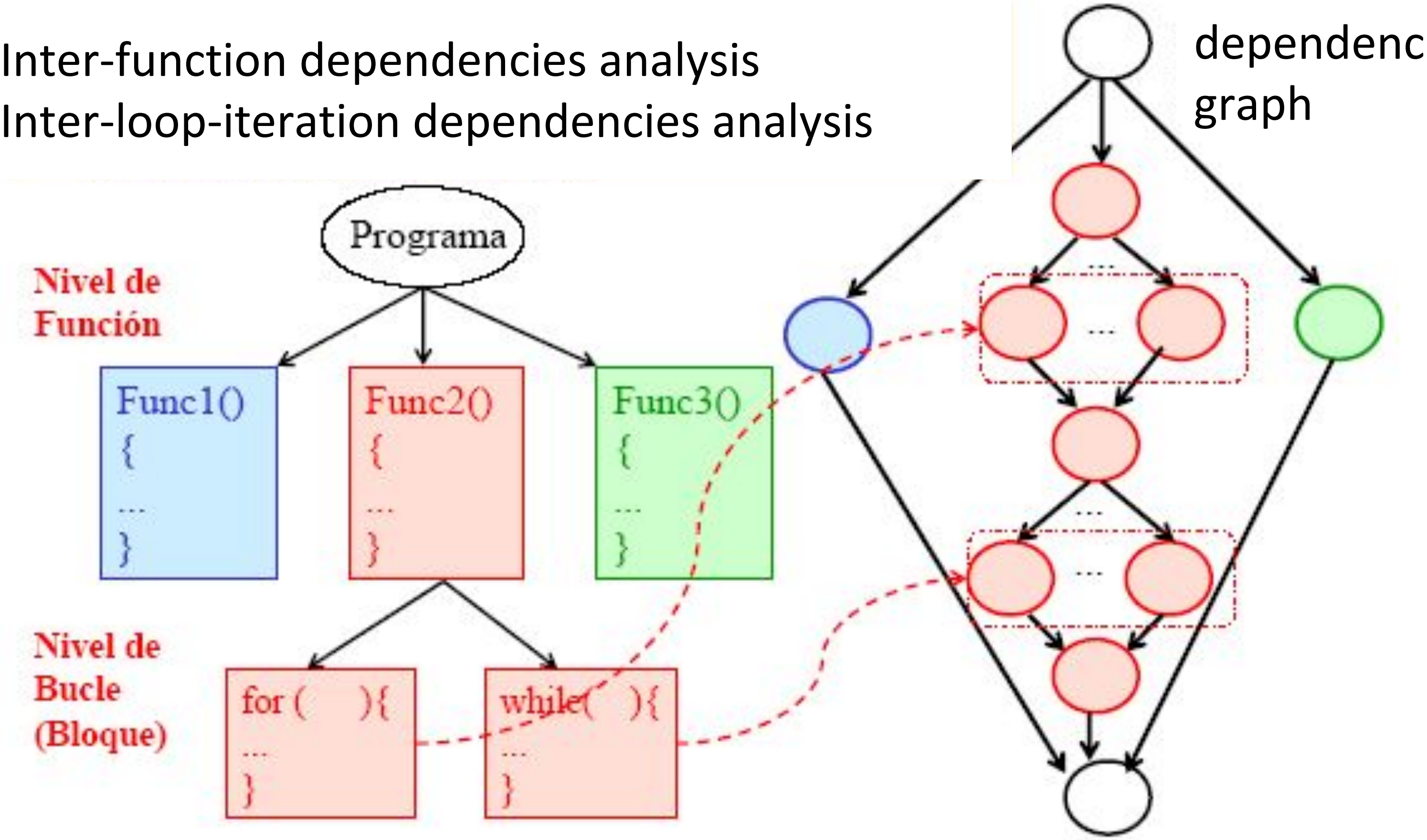
Parallelization process

1. Independent tasks **decomposition**
2. Task **assignment** to threads and/or processes.
3. Writing the parallel **code**
4. Performance evaluation



Parallelization process: independent tasks decomposition

- Inter-function dependencies analysis
- Inter-loop-iteration dependencies analysis



Task dependencies graph

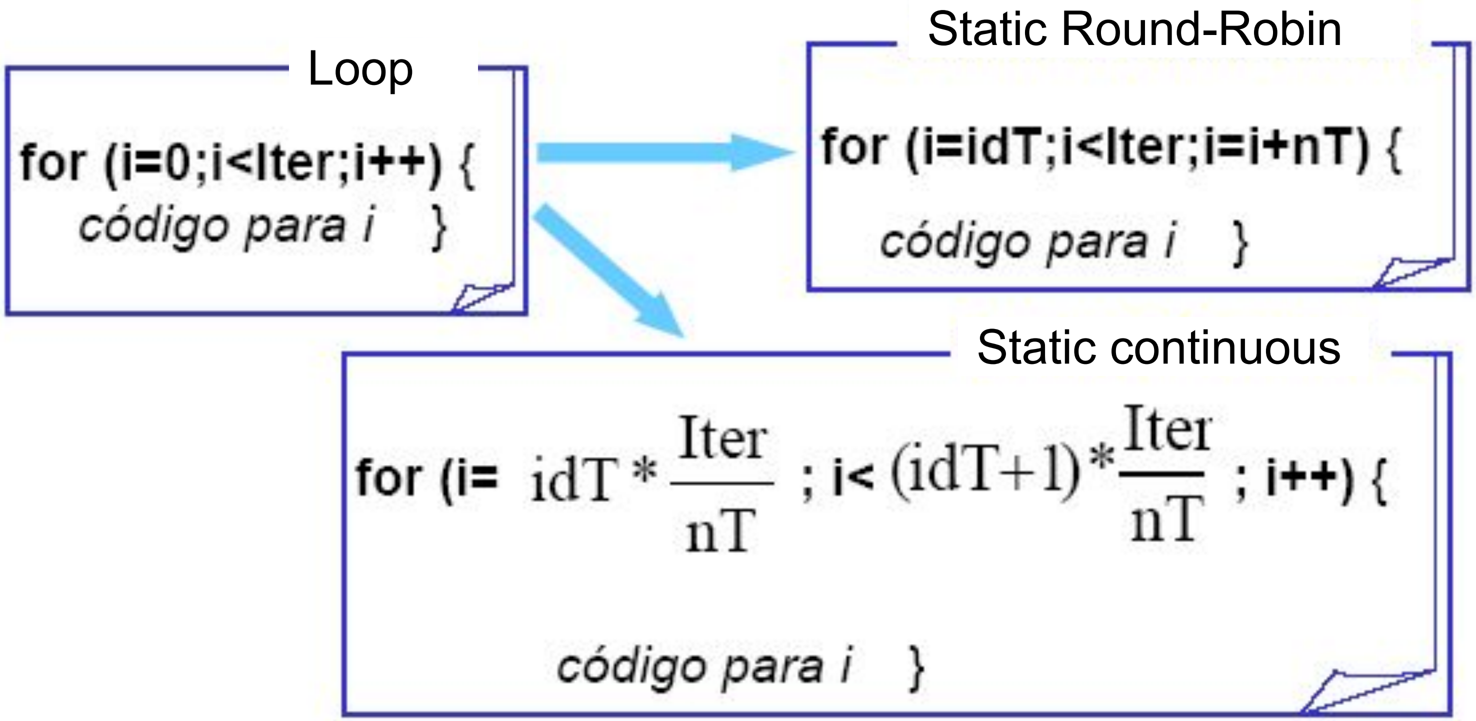
Techniques and procedures

Parallelization process: Tasks assignment

- Usually: loop iteration iteraciones ⟶ threads hebras and functions/methods -> processes
- Granularity depends on
  - # processors
  - Relation between communication & synchronization time and bare computing time
- Inherent tradeoff in the workload: (no processors should wait to any other)
- Assignment types:
  - Dynamic (while executing) ⟶ Usefull if we don’t know the # of tasks.
  - Static (designed by programmer or compiler)

Parallelization process: Tasks assignment

- Static assignment



Loop

```
for (i=0;i<Iter;i++) {
    código para i    }
```

Static Round-Robin

```
for (i=idT;i<Iter;i=i+nT) {
    código para i    }
```

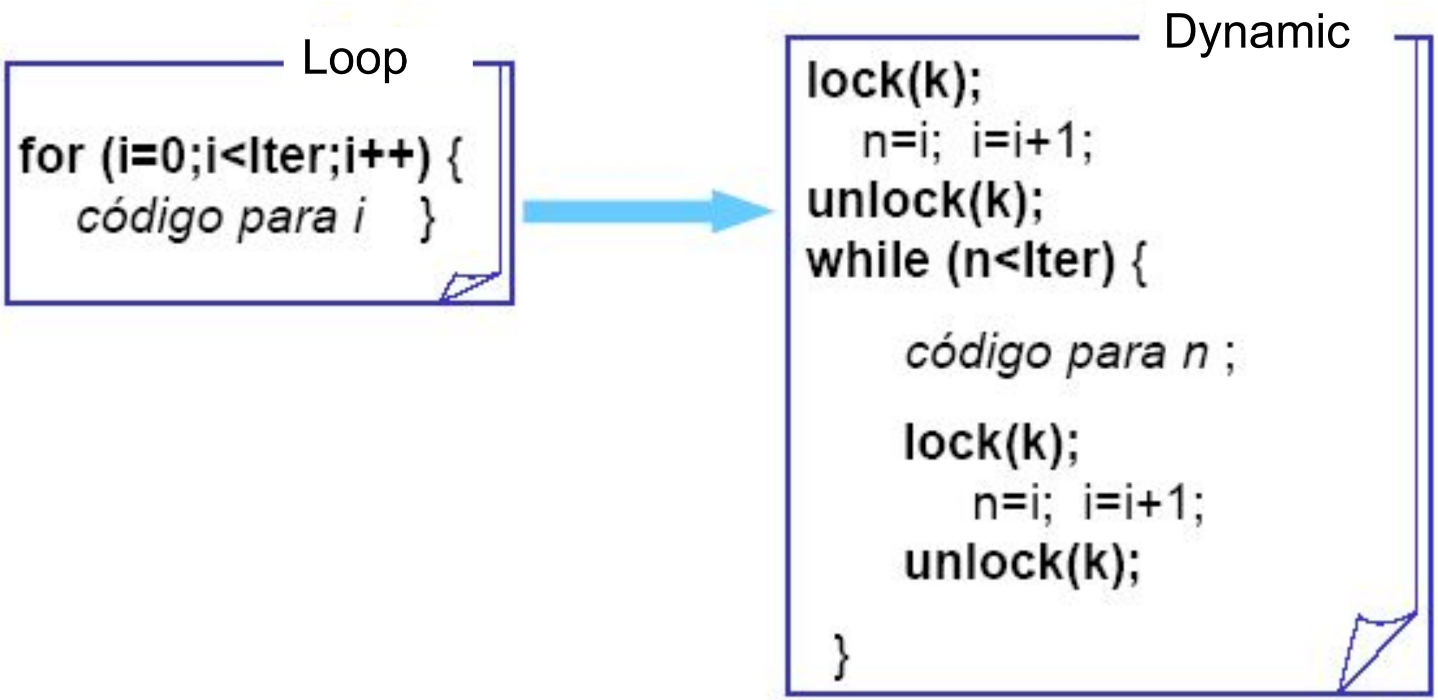
Static continuous

$$\text{for (i=}\ \mathrm{idT} * \frac{\mathrm{Iter}}{\mathrm{nT}}\ ;\ \text{i<}\ (\mathrm{idT}+1) * \frac{\mathrm{Iter}}{\mathrm{nT}}\ ;\ \text{i++) \{}$$

```
    código para i    }
```

Parallelization process: Tasks assignment

○ Dynamic assignment



Loop

```
for (i=0;i<Iter;i++) {
    código para i    }
```

Dynamic

```
lock(k);
   n=i;  i=i+1;
unlock(k);
while (n<Iter) {

      código para n ;

      lock(k);
          n=i;  i=i+1;
      unlock(k);

 }
```

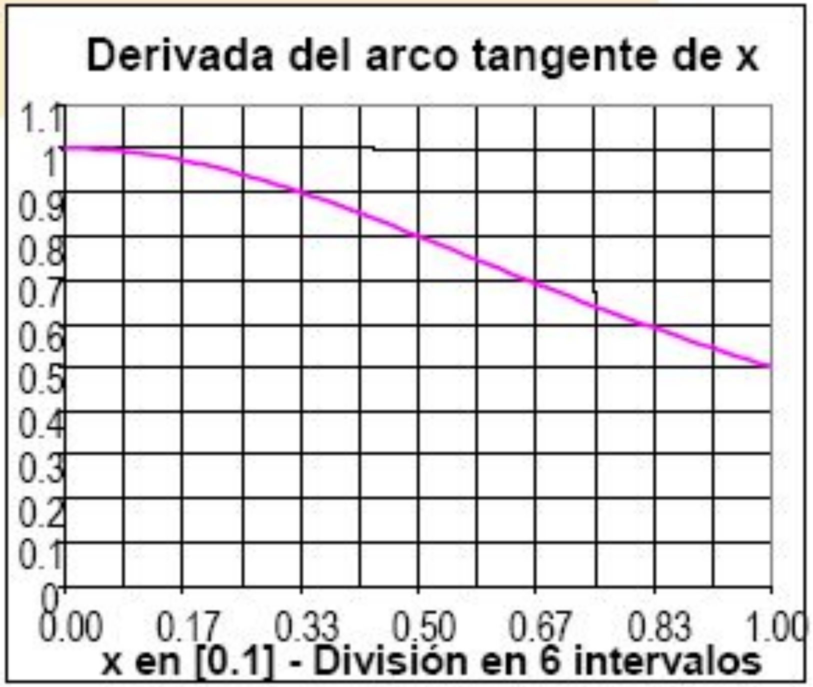
Parallelization process: writing parallel code

- It depends on:
  - Programming style: message passing, etc.
  - Programming mode
  - Starting point
  - Tool used for parallelism
  - Program structure

- A parallel program should include:
  - Processes/threads creation and destruction
  - Workload assignation
  - Communication and synchronization rutines

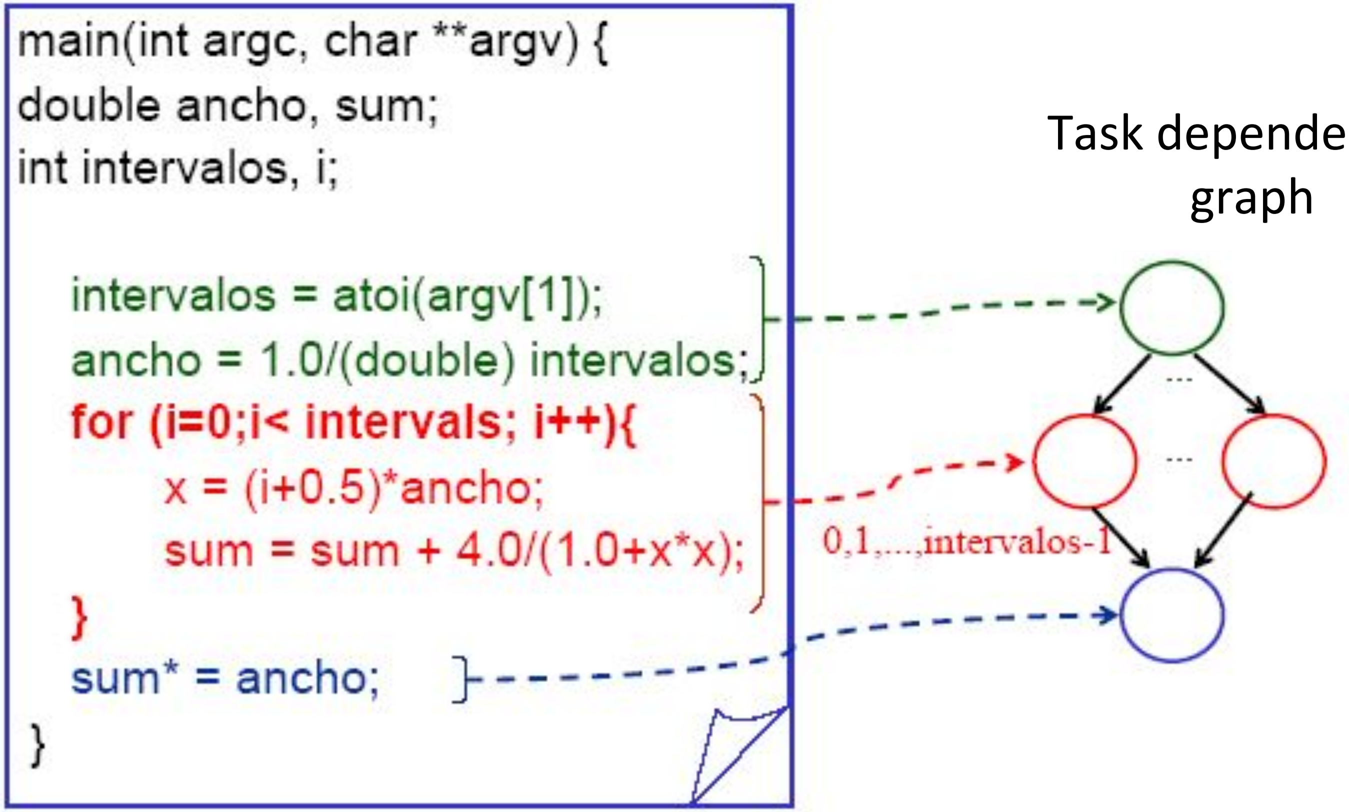
π calculus by task decomposition

$$\left.\begin{array}{l} \operatorname{arctg}'(x) = \dfrac{1}{1+x^2} \\ \operatorname{arctg}(1) = \dfrac{\pi}{4} \\ \operatorname{arctg}(0) = 0 \end{array}\right\} \Rightarrow \int_0^1 \frac{1}{1+x^2} = \operatorname{arctg}(x)\,\Big|_0^1 = \frac{\pi}{4} - 0$$



Pi can be calculated by means of numerical integration

π calculus by task decomposition



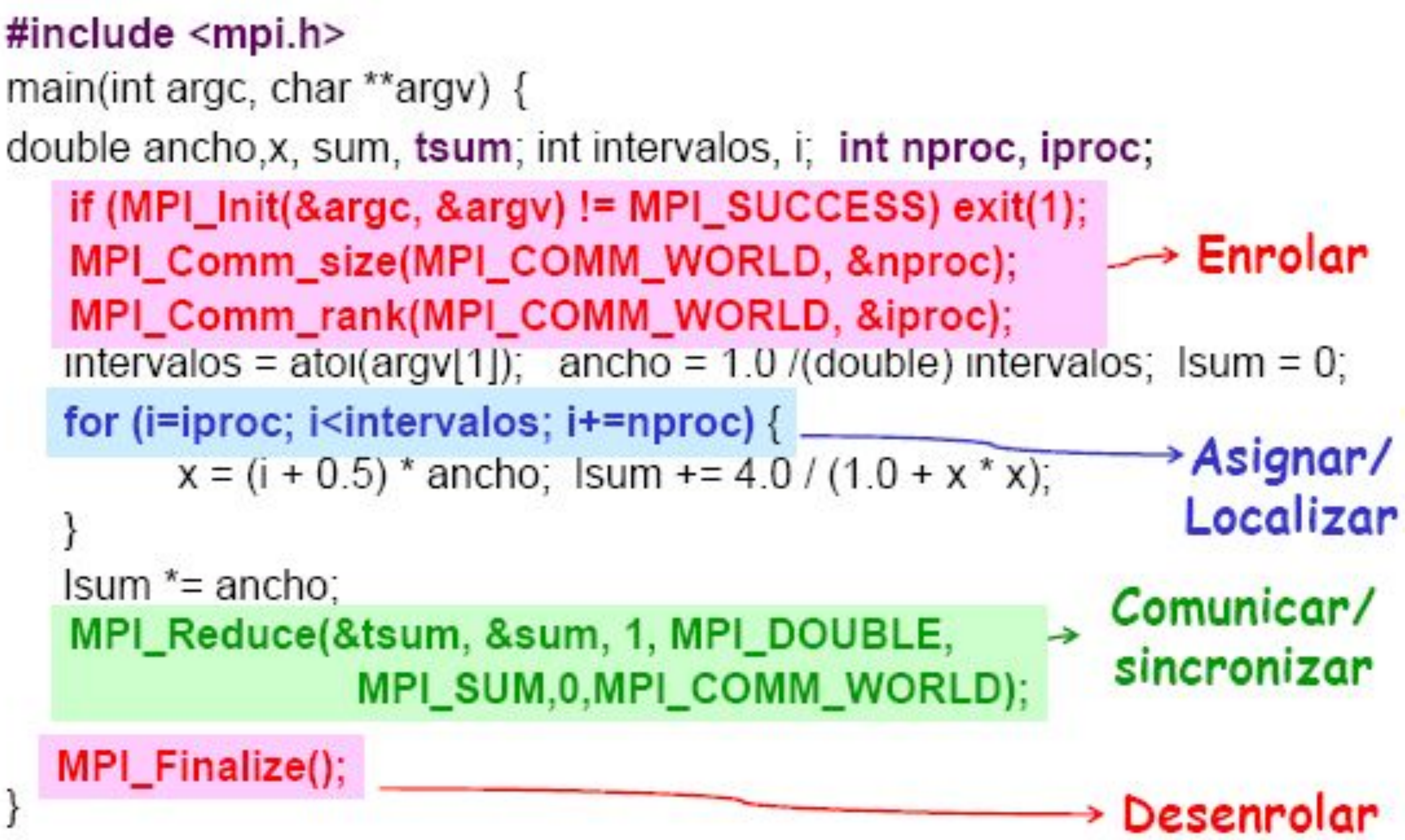
```
main(int argc, char **argv) {
double ancho, sum;
int intervalos, i;

    intervalos = atoi(argv[1]);
    ancho = 1.0/(double) intervalos;
    for (i=0;i< intervals; i++){
          x = (i+0.5)*ancho;
          sum = sum + 4.0/(1.0+x*x);
    }
    sum* = ancho;
}
```

Task dependencies graph

π calculus by task decomposition

- Static **assignation** of each loop iteration (Round Robin assign.)
- Parallel code signature
  - Programming style: Message passing
  - Programming mode: SPMD
  - Starting from: sequential version of the code
  - Tool: MPI
  - Program structure: Data parallelism or Divide and Conquer

π calculus by task decomposition using MPI

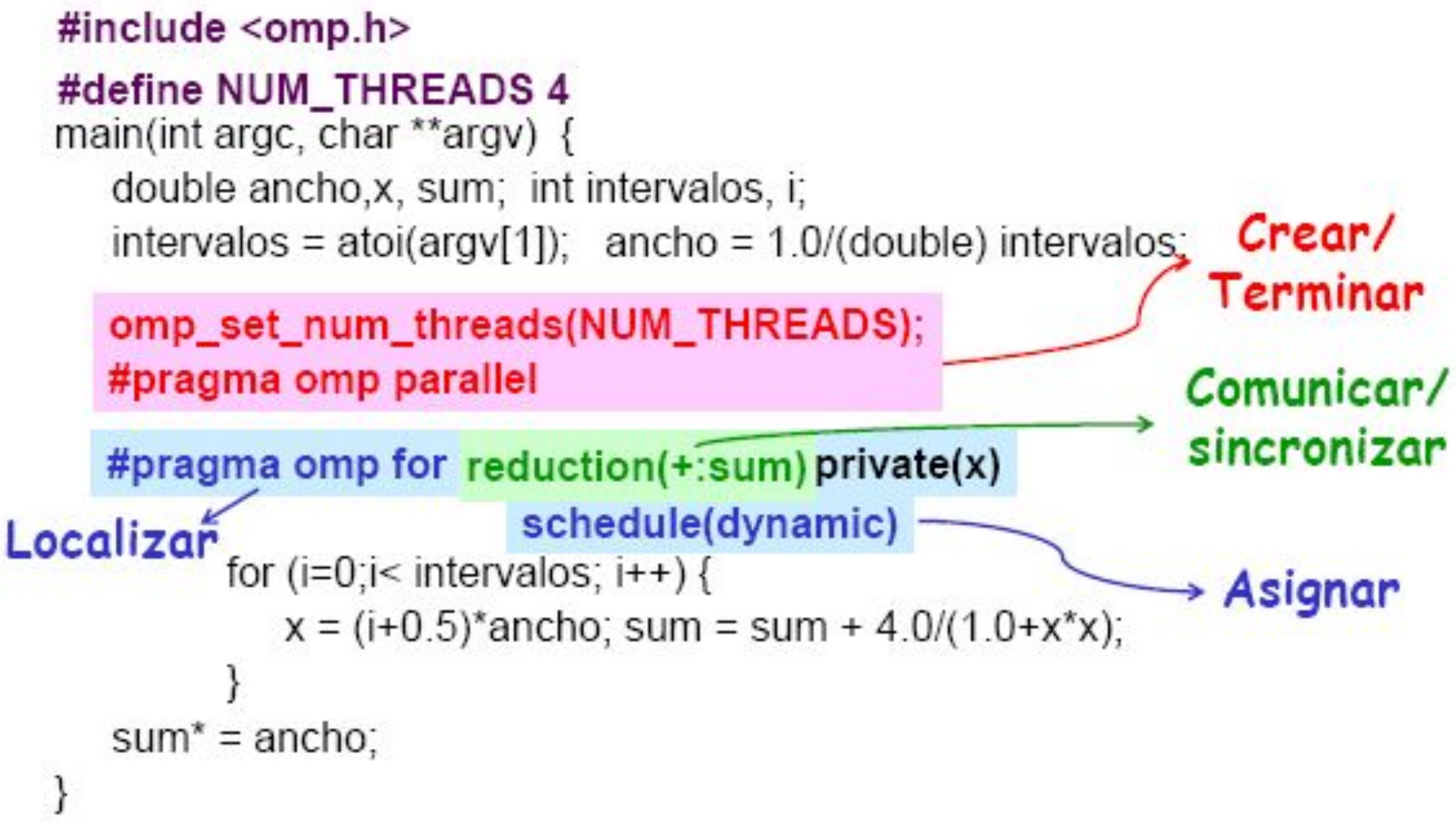


```
#include <mpi.h>
main(int argc, char **argv)  {
double ancho,x, sum, tsum; int intervalos, i;  int nproc, iproc;
    if (MPI_Init(&argc, &argv) != MPI_SUCCESS) exit(1);
    MPI_Comm_size(MPI_COMM_WORLD, &nproc);
    MPI_Comm_rank(MPI_COMM_WORLD, &iproc);
    intervalos = atoi(argv[1]);   ancho = 1.0 /(double) intervalos;  lsum = 0;
    for (i=iproc; i<intervalos; i+=nproc) {
            x = (i + 0.5) * ancho;  lsum += 4.0 / (1.0 + x * x);
    }
    lsum *= ancho;
    MPI_Reduce(&tsum, &sum, 1, MPI_DOUBLE,
                    MPI_SUM,0,MPI_COMM_WORLD);
   MPI_Finalize();
}
```

π calculus by task decomposition

- ○ Dynamic **assignation** of each loop iteration
- ○ Parallel code signature:
  - ■ Programming style: directives + API (OpenMP)
  - ■ Programming mode: SPMD
  - ■ Starting from: sequential version of the code
  - ■ Tool: OpenMP
  - ■ Program structure: Data parallelism or Divide and Conquer

π calculus by task decomposition using OpenMP



```
#include <omp.h>
#define NUM_THREADS 4
main(int argc, char **argv)  {
     double ancho,x, sum;  int intervalos, i;
     intervalos = atoi(argv[1]);   ancho = 1.0/(double) intervalos;
     omp_set_num_threads(NUM_THREADS);
     #pragma omp parallel
     #pragma omp for reduction(+:sum) private(x)
                         schedule(dynamic)
          for (i=0;i< intervalos; i++) {
               x = (i+0.5)*ancho; sum = sum + 4.0/(1.0+x*x);
          }
     sum* = ancho;
}
```