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Parallel & Distributed Computing Techniques

6/12/2011

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3 Synchronous Computation

4 Embarrassingly Parallel Computations

5 Pipelined Computations

6 Load Balancing & Termination Detection

1. Message-Passing Computing

- **Programming a message-passing multicomputer can be achieved by:**
  - Designing a special parallel programming language
  - Extending the syntax/reserved words of an existing sequential high-level language to handle message-passing.
  - Using an existing sequential high-level language and providing a library of external procedures for message-passing.

1. Message-Passing Computing

- **Message-passing programming using user-level message-passing libraries needs two mechanisms:**
  - A method of creating separate processes for execution on different computers
  - A method of sending and receiving messages.

1. Message-Passing Computing

❖ Static process creation:

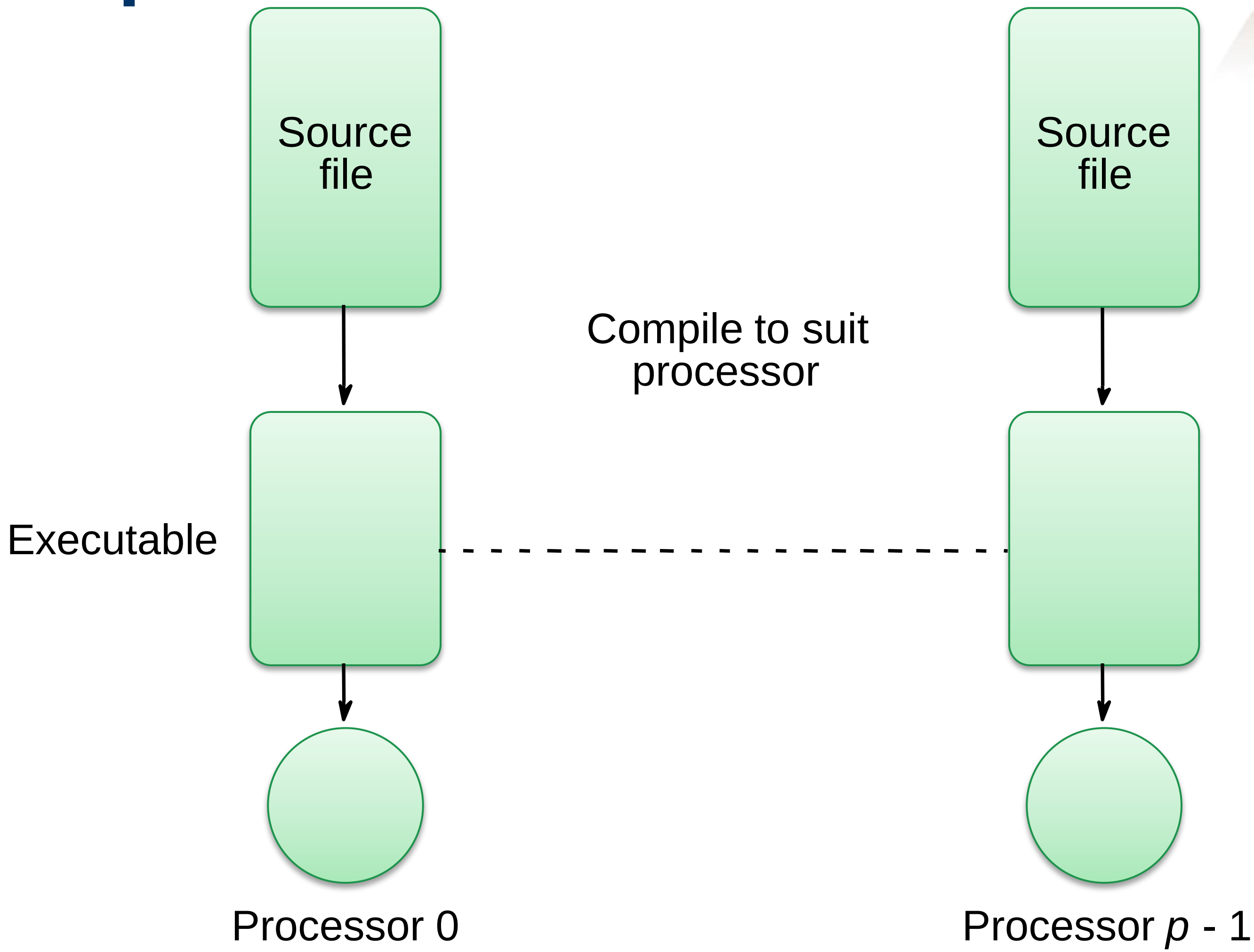
- All processes are specified before execution.
- The system will execute a fixed number of processes.

❖ Dynamic process creation

- Process can be created and their execution initiated during execution of other processes.
- Number of processes may vary during execution

1. Message-Passing Computing

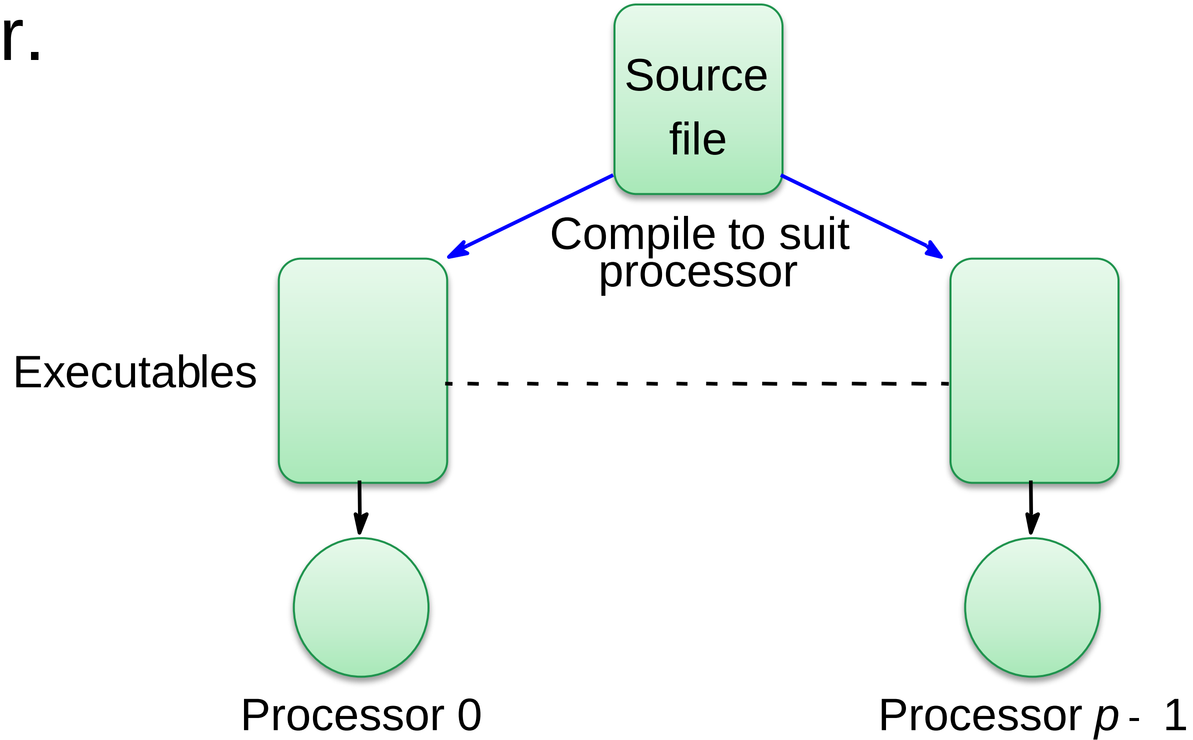
❖ Static process creation: MPMD model



1. Message-Passing Computing

❖ Static process creation: SPMD model

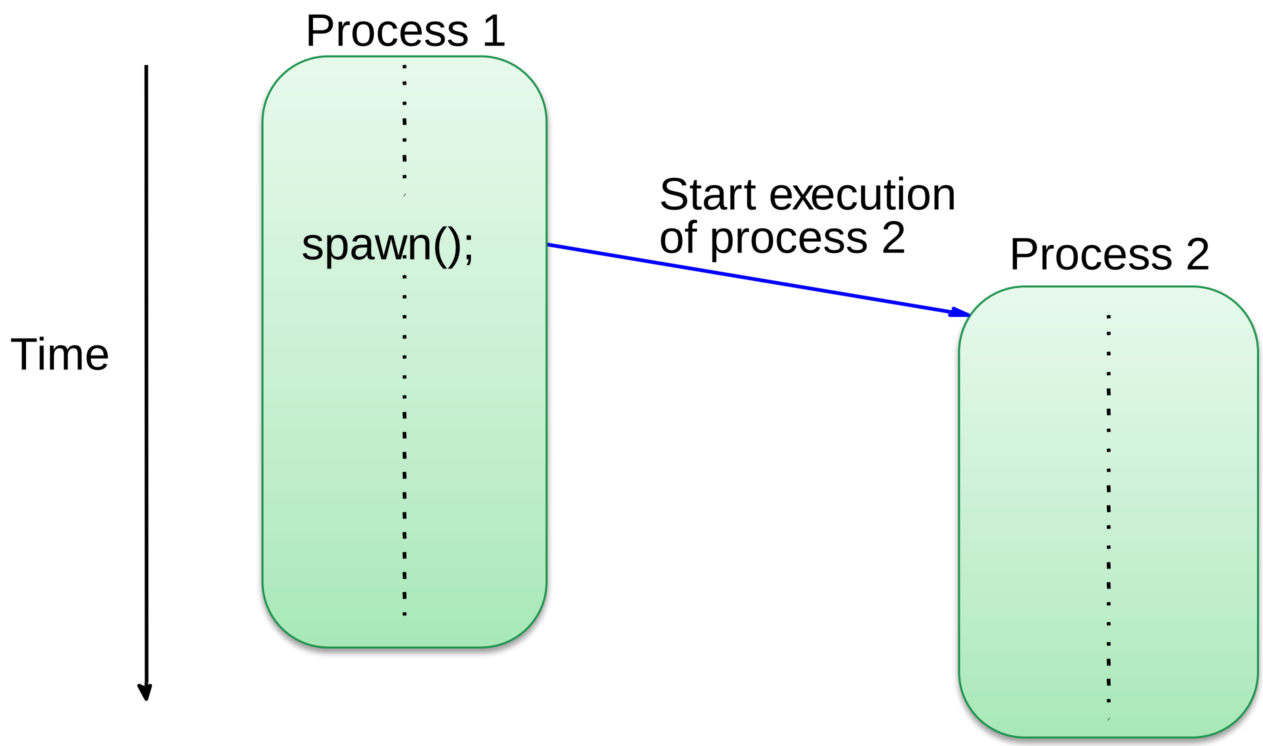
- Different processes merged into one program. Control statements select different parts for each processor to execute. All executables started together.



1. Message-Passing Computing

❖ Dynamic process creation: MPMD model

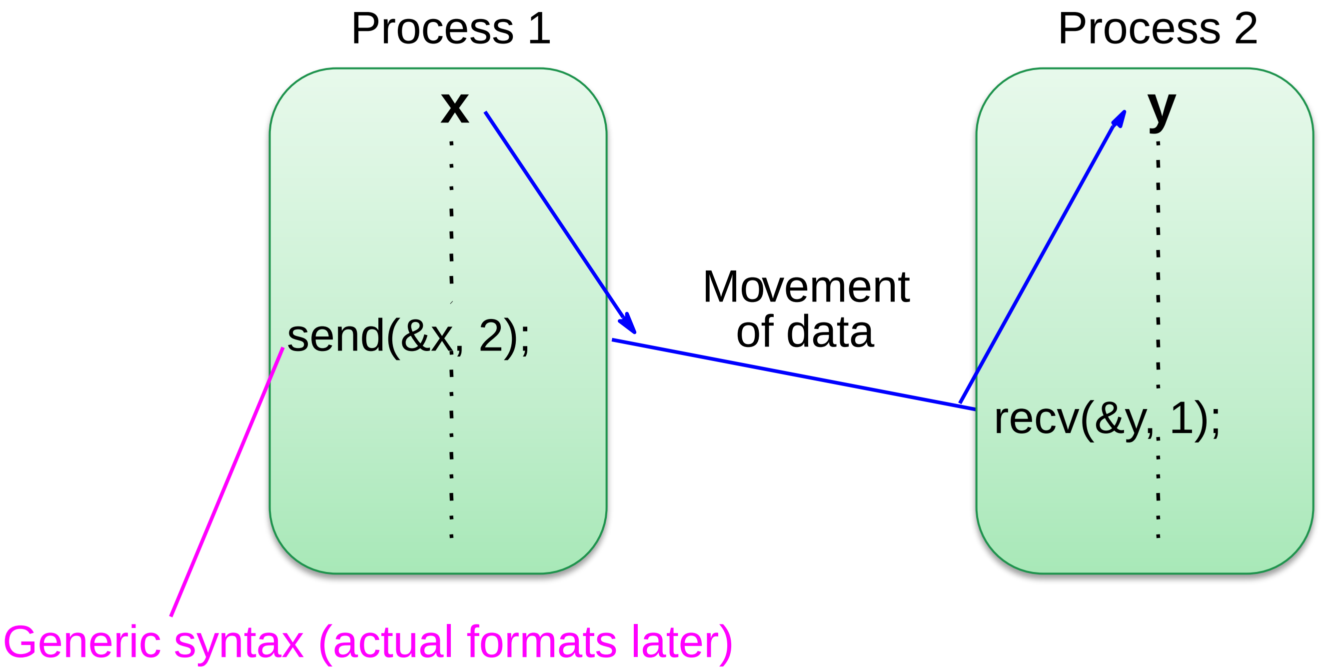
- Separate programs for each processor. One processor executes master process. Other processes started from within master process.



1. Message-Passing Computing

❖ Basic "point-to-point" Send and Receive Routines:

- Passing a message between processes using send() and recv() library calls:



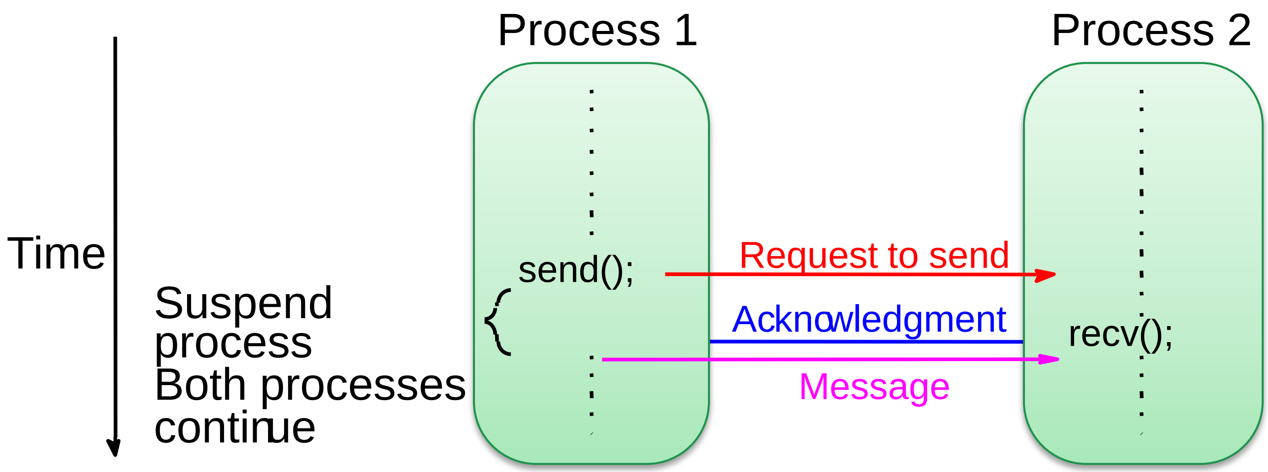
1. Message-Passing Computing

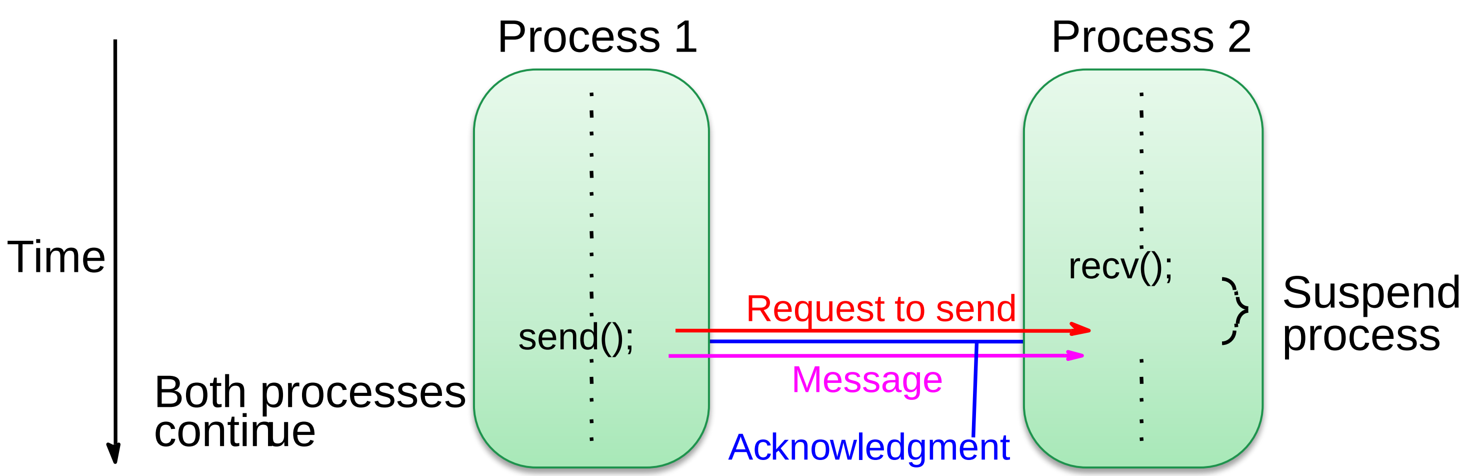
- **Synchronous Message Passing:**
  - Routines that actually return when message transfer completed.
- **Synchronous send routine:**
  - Waits until complete message can be accepted by the receiving process before sending the message.
- **Synchronous receive routine:**
  - Waits until the message it is expecting arrives.

➢ Synchronous routines intrinsically perform two actions: transfer data and synchronize processes.

1. Message-Passing Computing

❖ Synchronous Message Passing:





1. Message-Passing Computing

❖ MPI Definitions of Blocking and Non-Blocking:

- Blocking - return after their local actions complete, though the message transfer may not have been completed.
- Non-blocking - return immediately.
- Assumes that data storage used for transfer not modified by subsequent statements prior to being used for transfer, and it is left to the programmer to ensure this.

1. Message-Passing Computing

- **Message Tag**
- **“Group” message passing routines**
  - Broadcast
  - Gather
  - Scatter

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2. Partitioning & Divide-And-Conquer Strategies

❖ Partitioning

- Partitioning simply divides the problem into parts.

❖ Divide and Conquer

- Characterized by dividing problem into sub-problems of same form as larger problem. Further divisions into still smaller sub-problems, usually done by recursion.

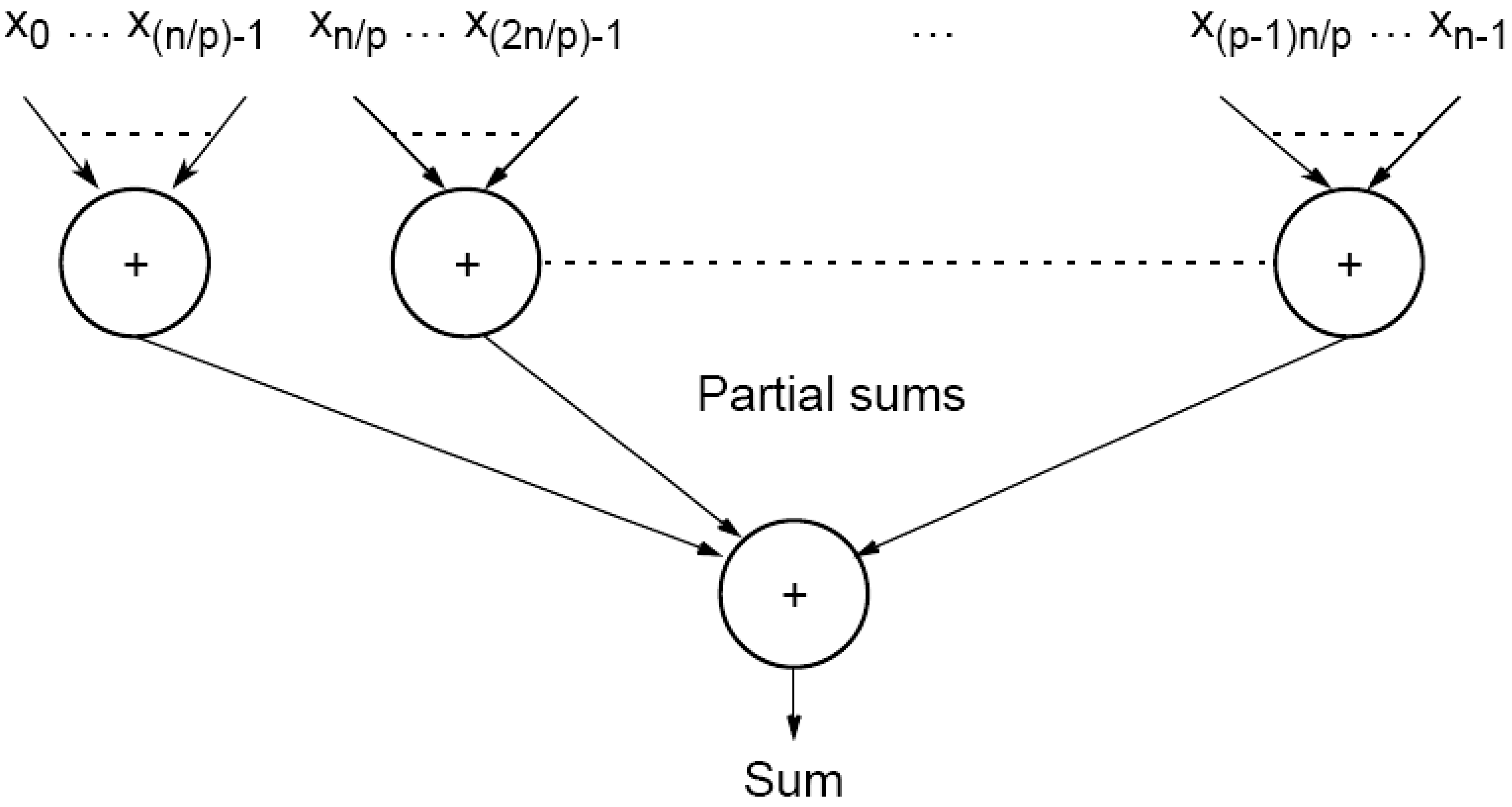
2. Partitioning & Divide-And-Conquer Strategies

❖ Partitioning/Divide and Conquer Examples

- Operations on sequences of number such as simply adding them together
- Several sorting algorithms can often be partitioned or constructed in a recursive fashion
- Numerical integration
- N-body problem

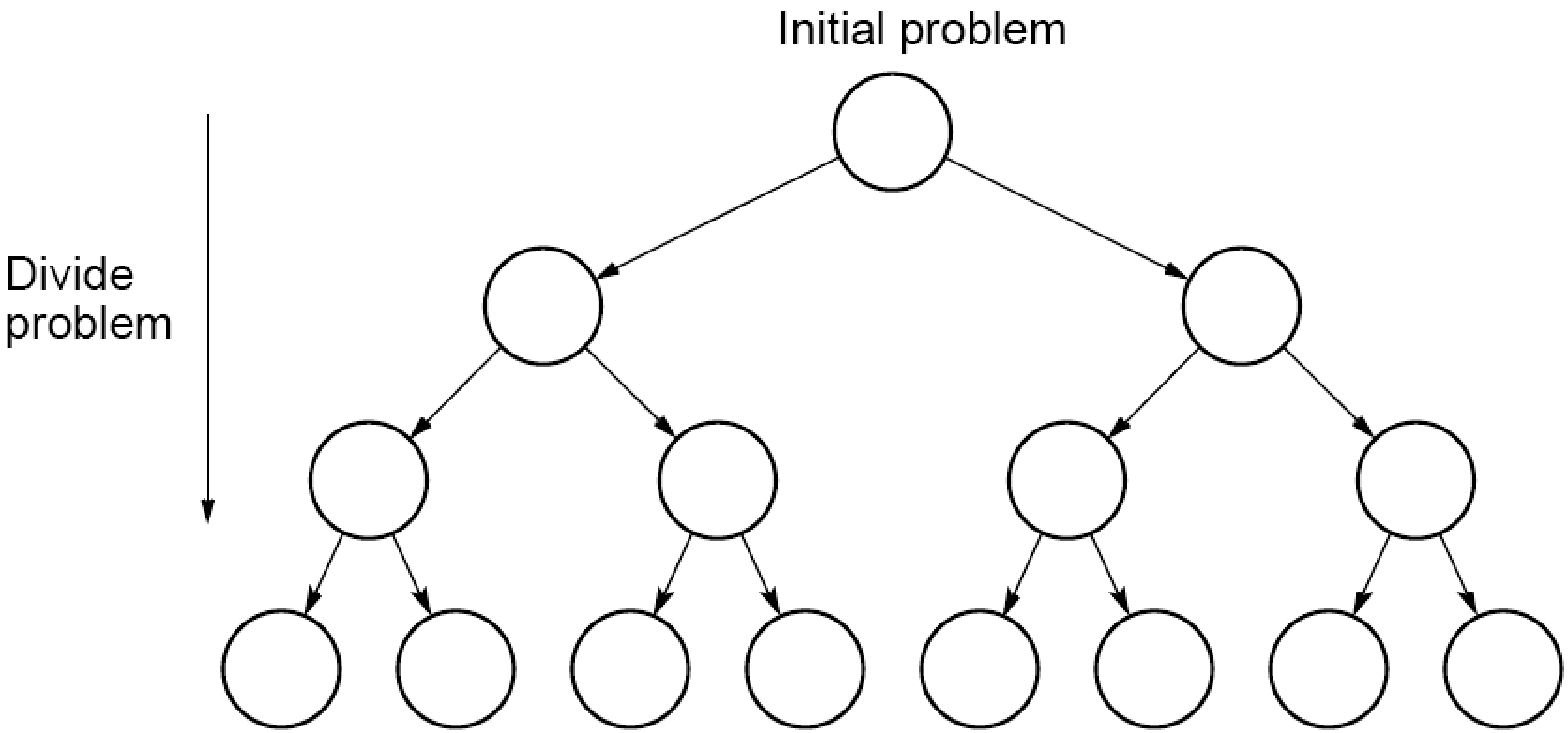
2. Partitioning & Divide-And-Conquer Strategies

❖ **Partitioning a sequence of numbers into parts and adding the parts**



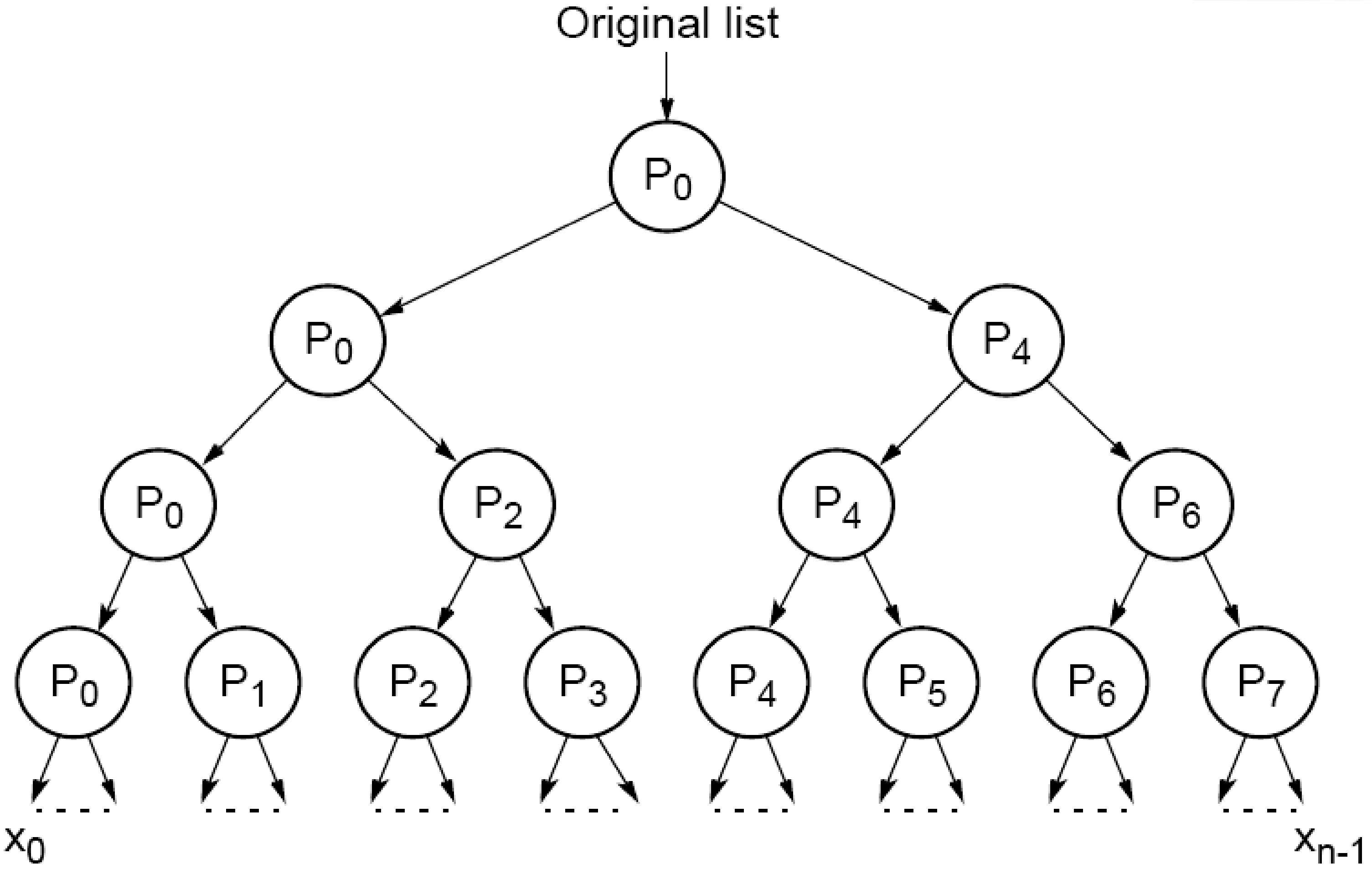
2. Partitioning & Divide-And-Conquer Strategies

❖ Tree construction



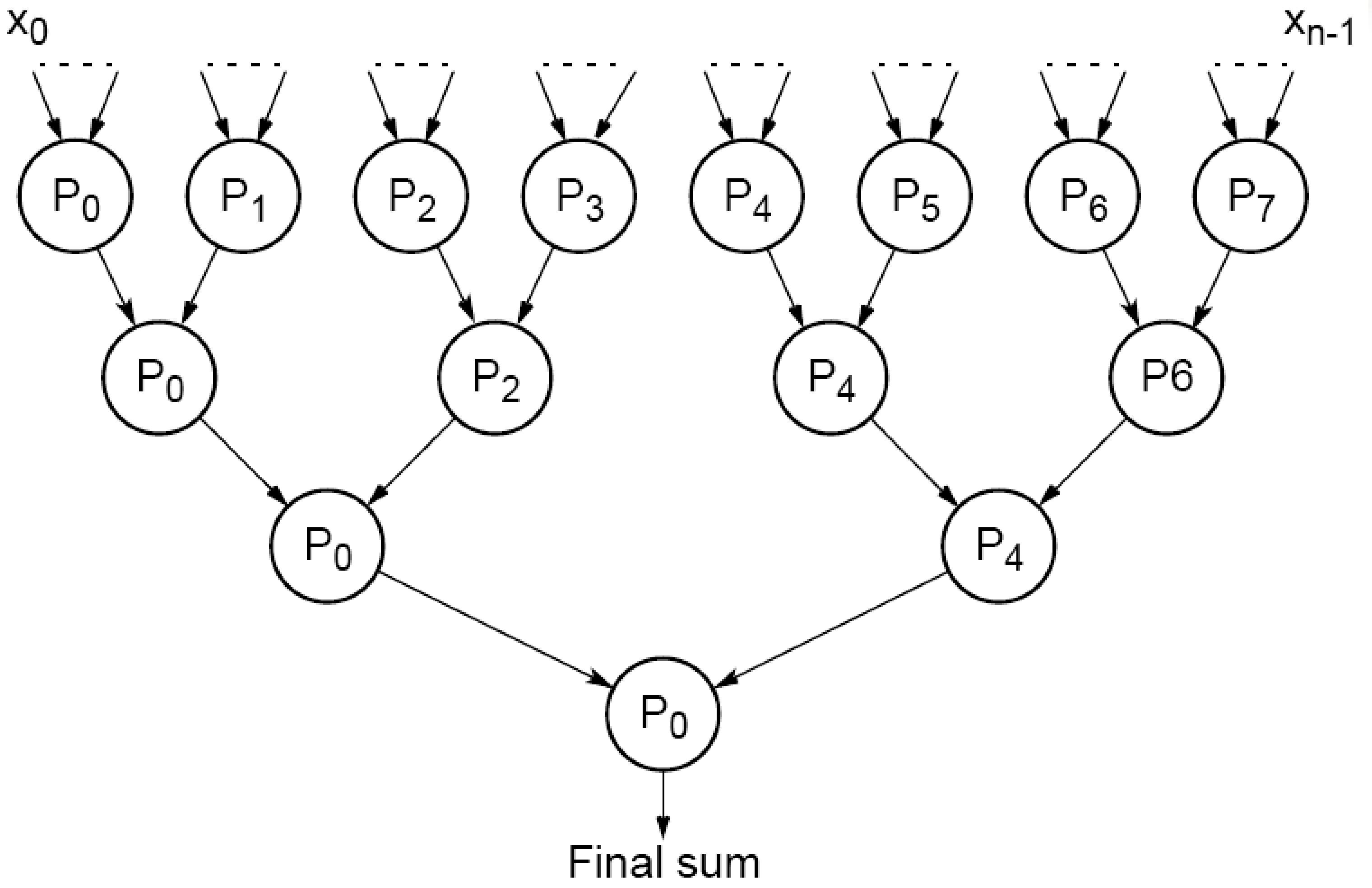
2. Partitioning & Divide-And-Conquer Strategies

❖ Dividing a list into parts



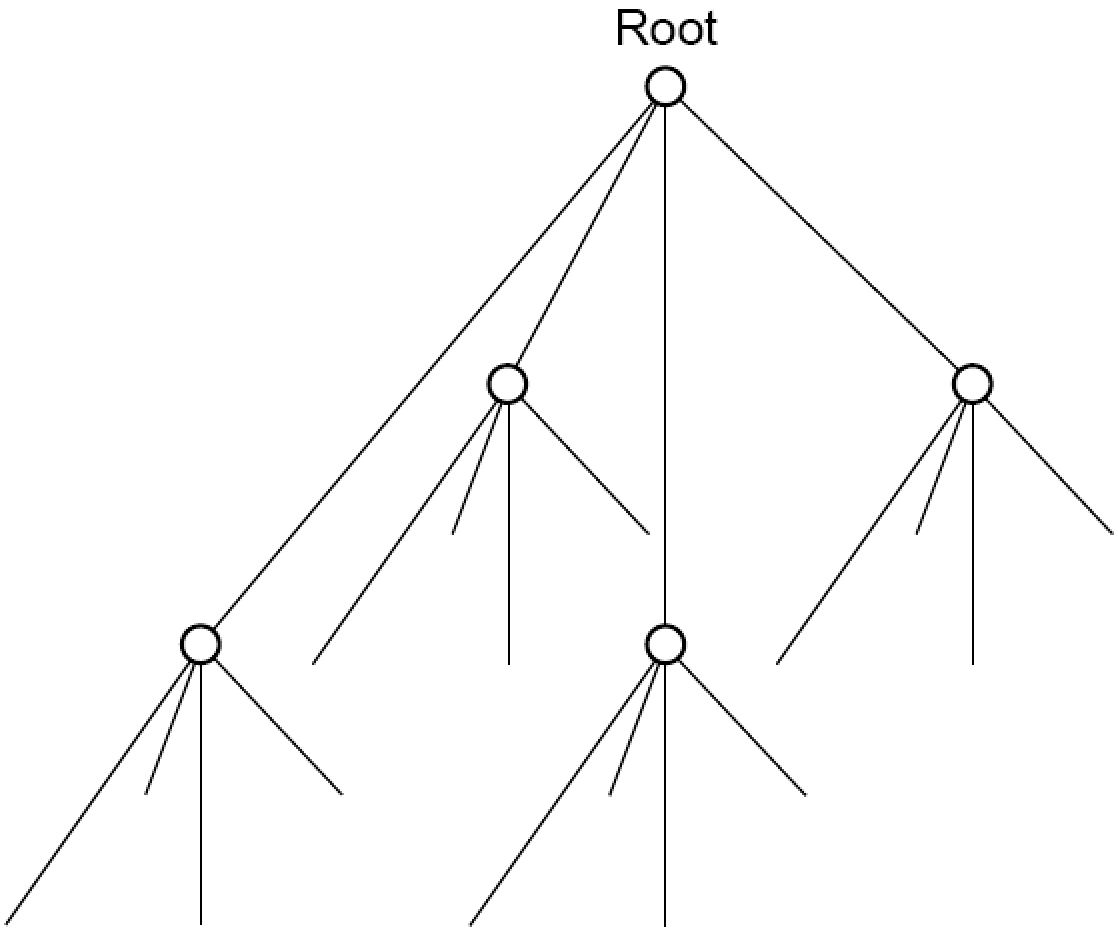
2. Partitioning & Divide-And-Conquer Strategies

❖ Partial summation



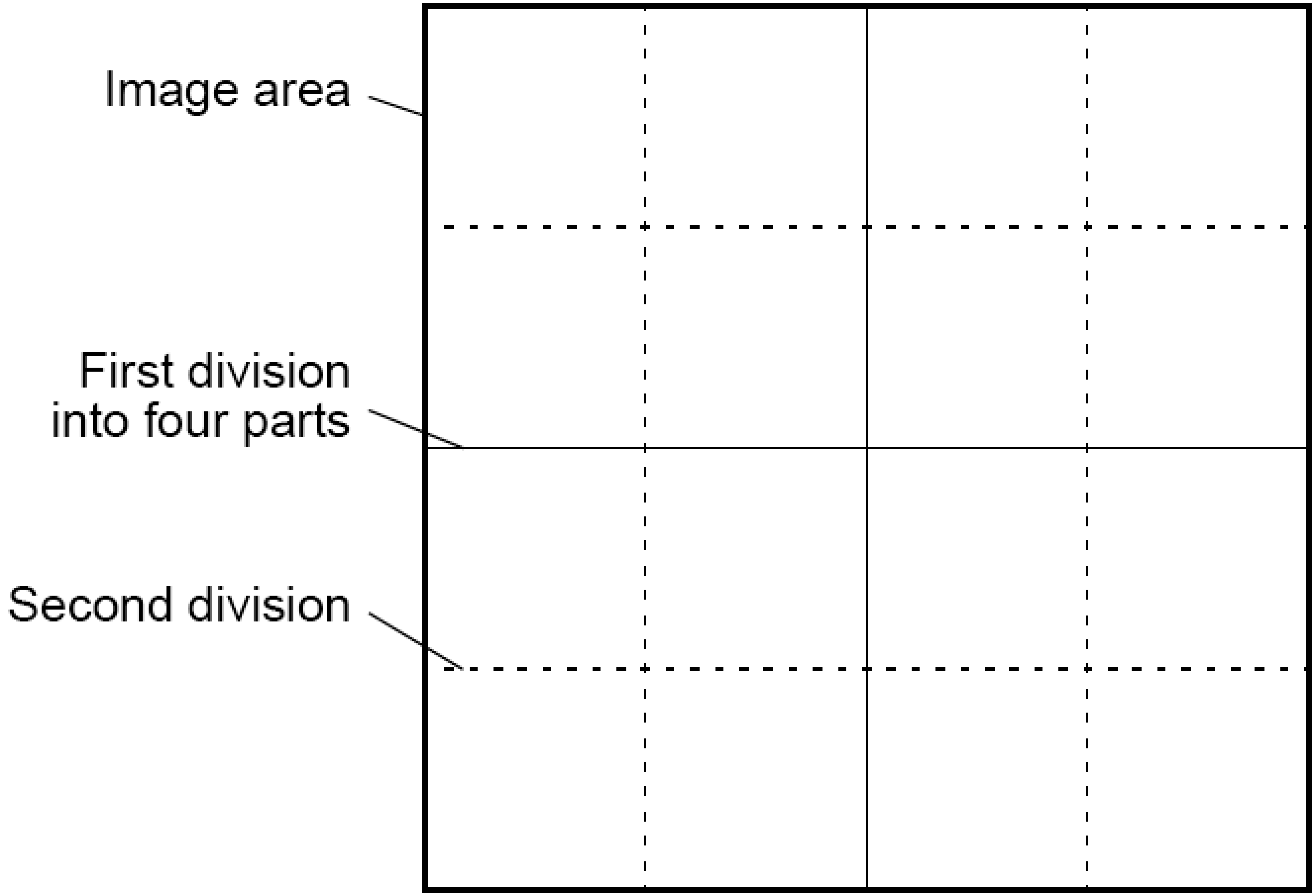
2. Partitioning & Divide-And-Conquer Strategies

❖ Quadtree



2. Partitioning & Divide-And-Conquer Strategies

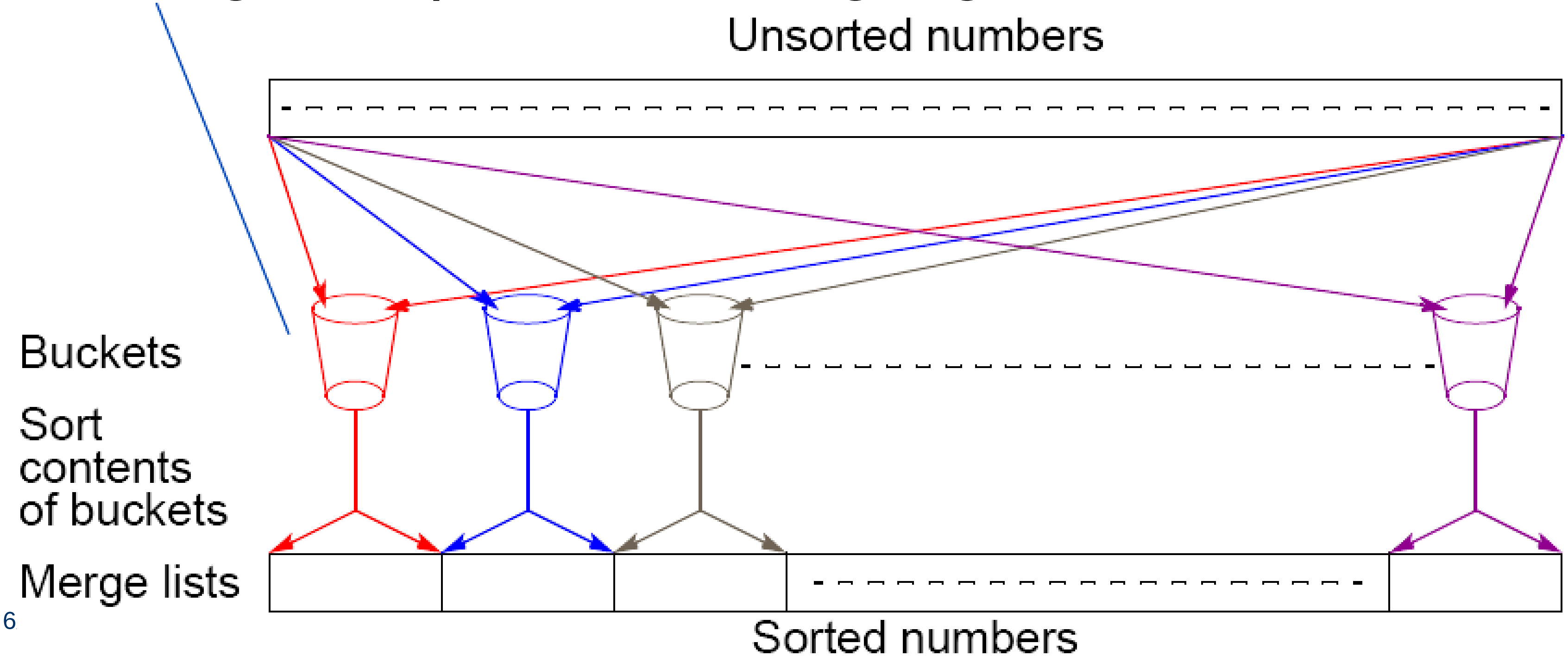
❖ Dividing an image



2. Partitioning & Divide-And-Conquer Strategies

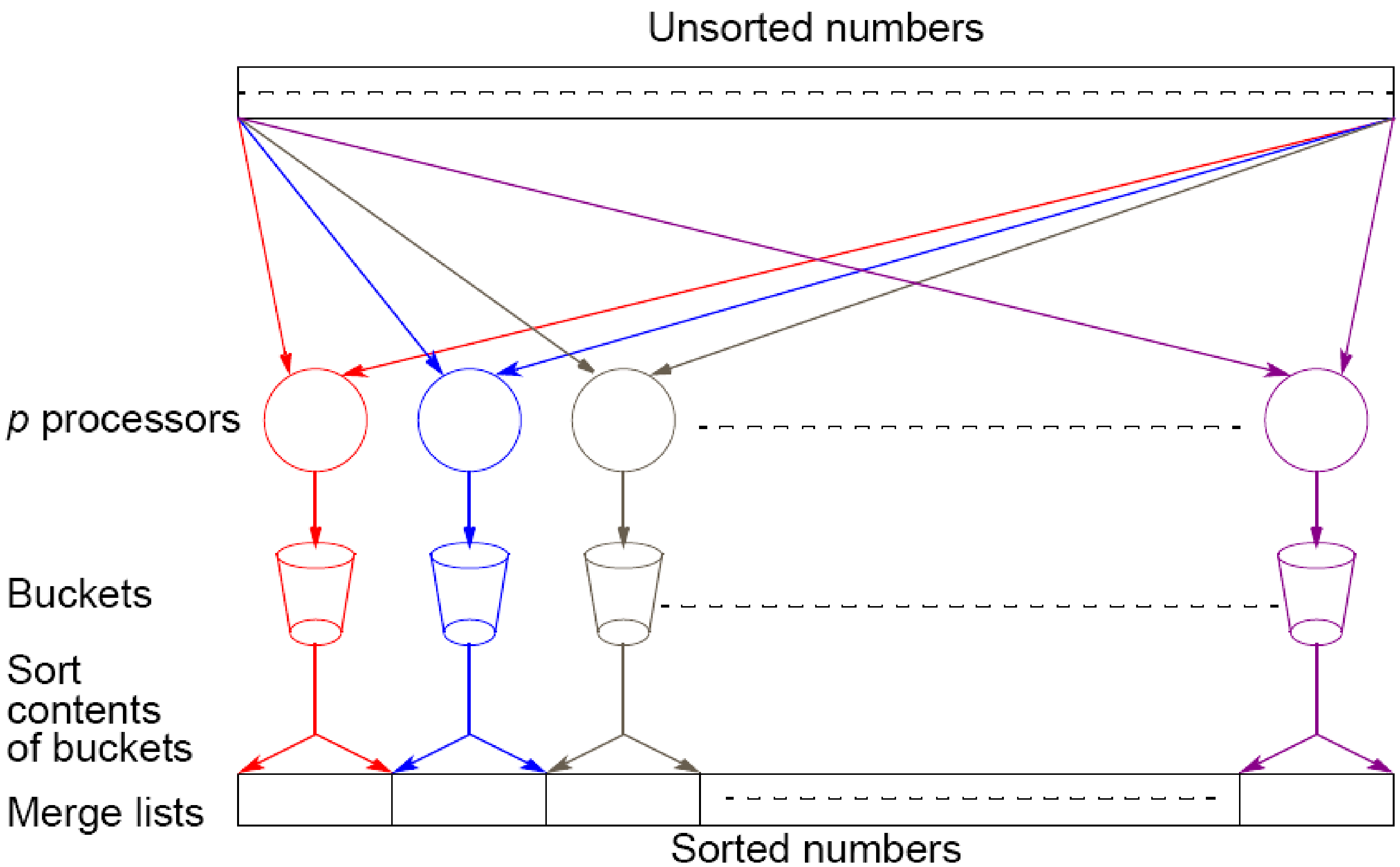
❖ Bucket sort

- One “bucket” assigned to hold numbers that fall within each region. Numbers in each bucket sorted using a sequential sorting algorithm.



2. Partitioning & Divide-And-Conquer Strategies

- ❖ **Parallel version of bucket sort – Simple approach**



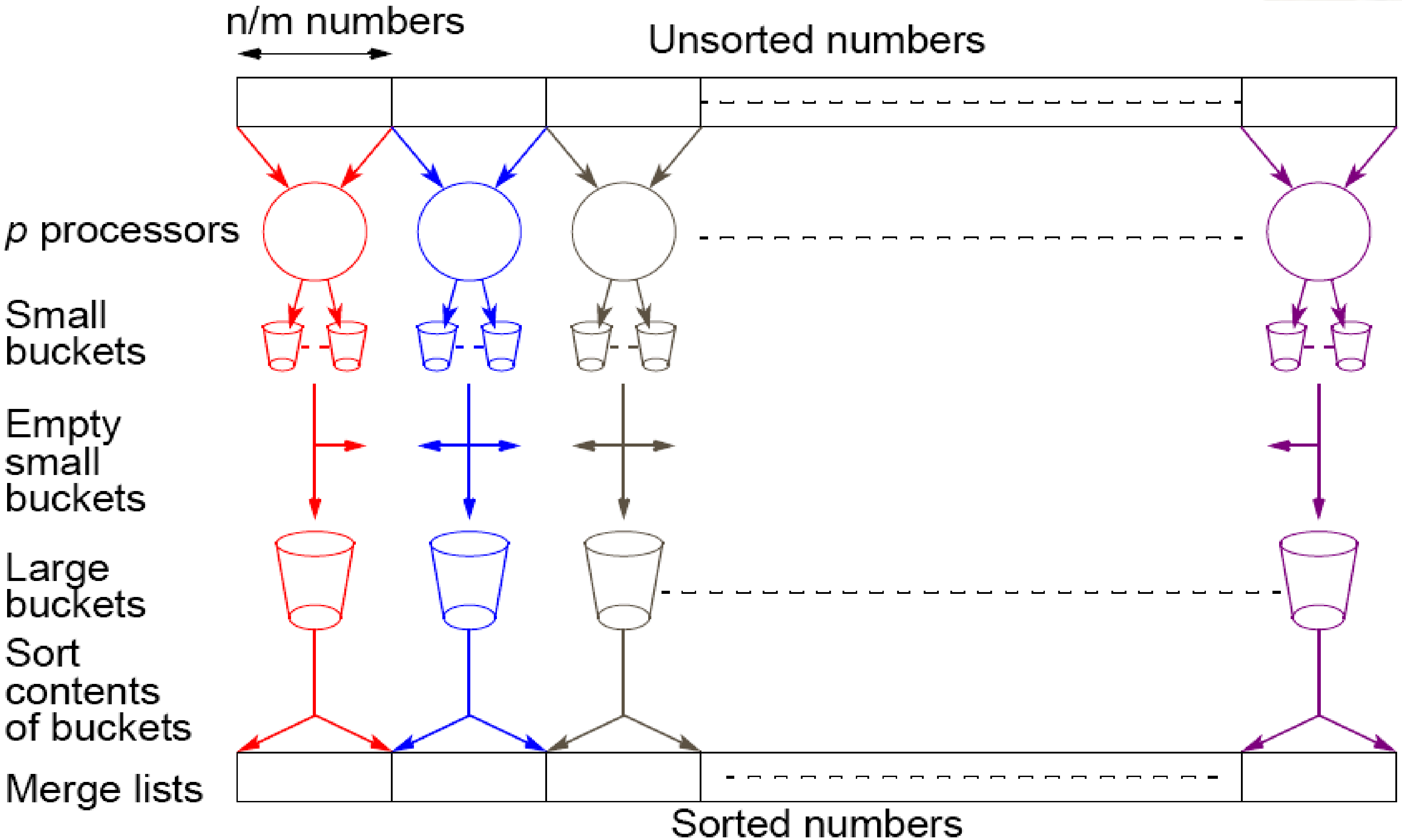
2. Partitioning & Divide-And-Conquer Strategies

❖ Further Parallelization

- Partition sequence into *m* regions, one region for each processor.
- Each processor maintains *p* “small” buckets and separates numbers in its region into its own small buckets.
- Small buckets then emptied into *p* final buckets for sorting, which requires each processor to send one small bucket to each of the other processors (bucket *i* to processor *i*).

2. Partitioning & Divide-And-Conquer Strategies

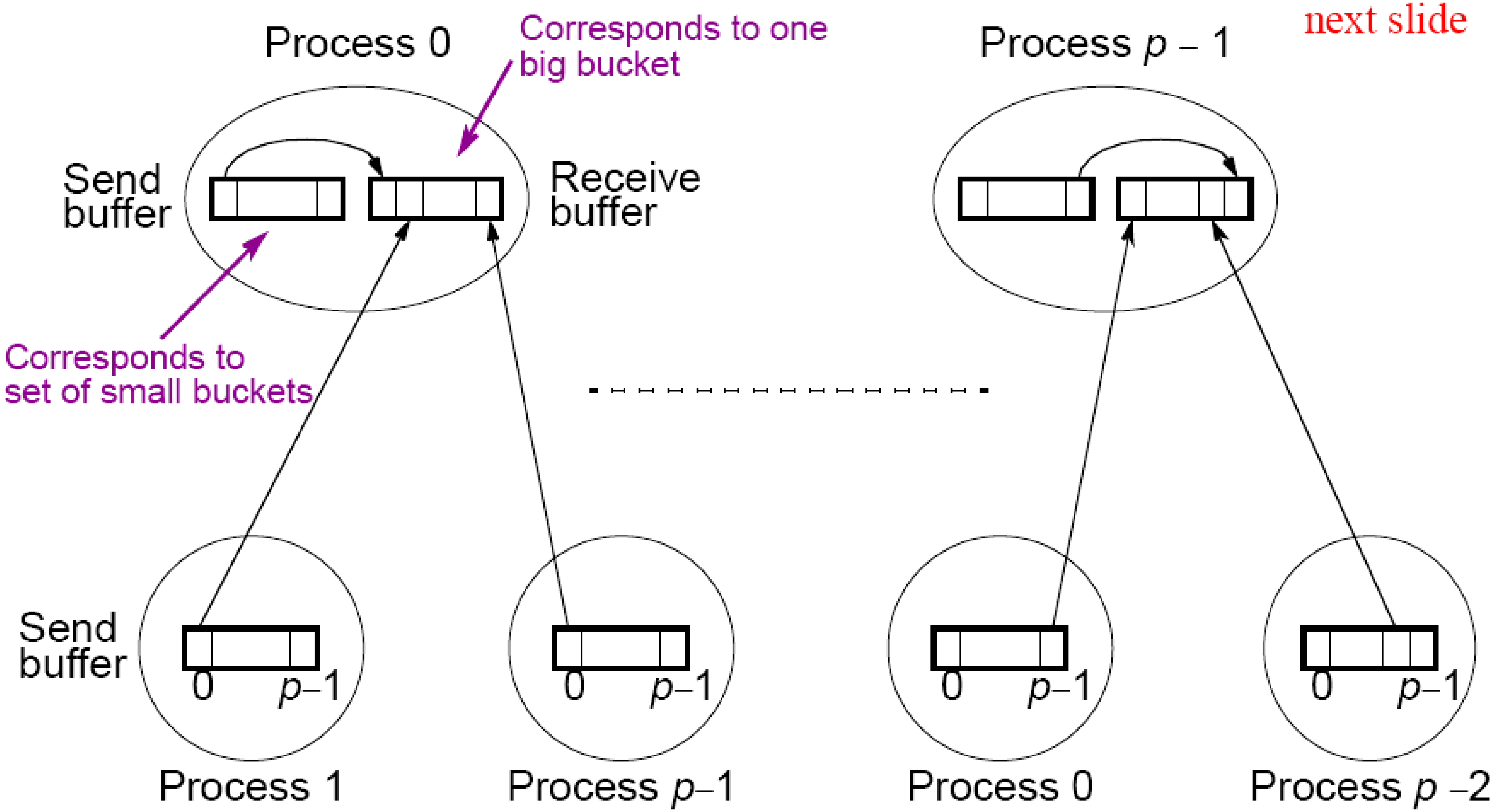
- **Another parallel version of bucket sort**



2. Partitioning & Divide-And-Conquer Strategies

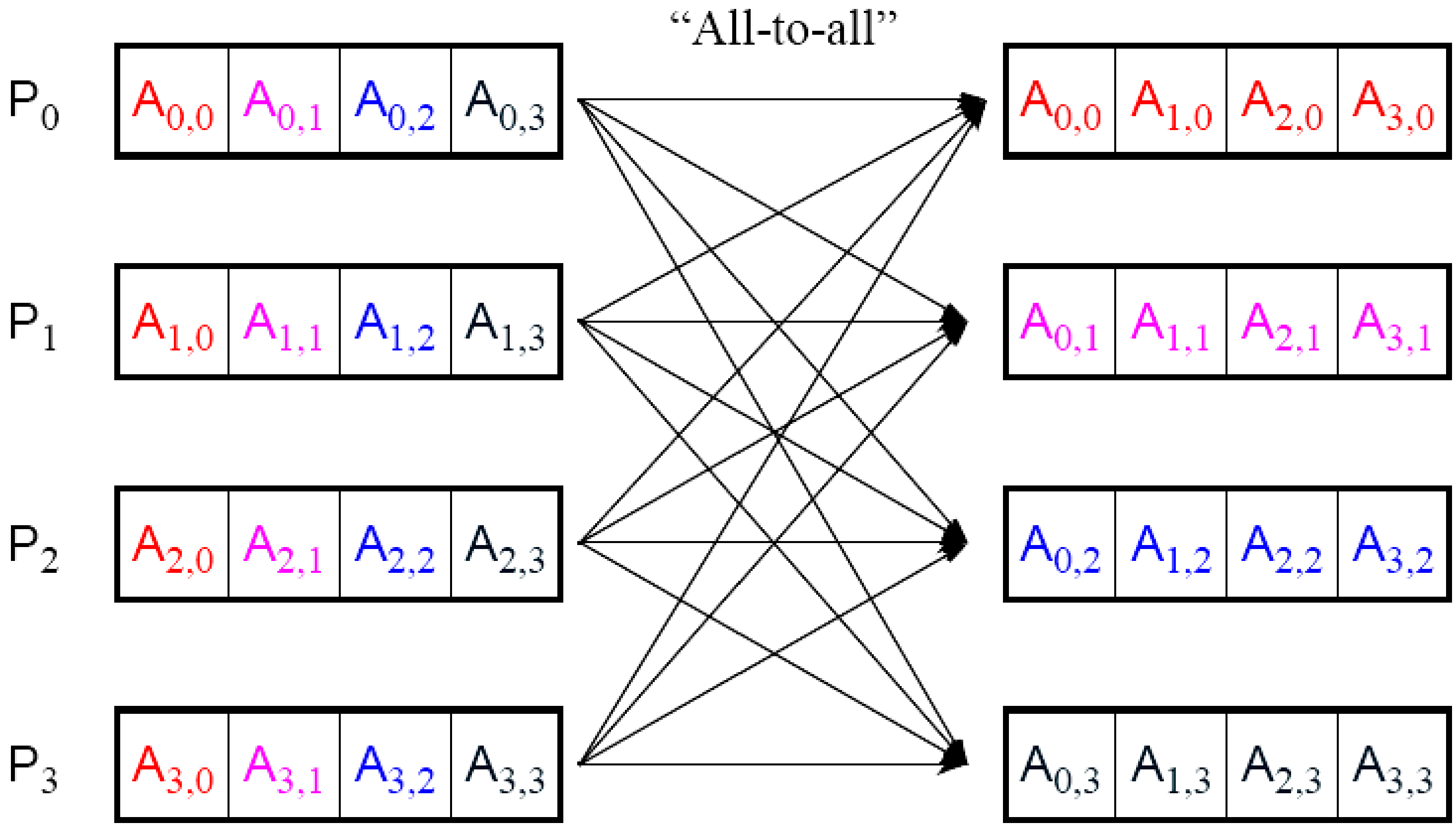
❖ "all-to-all" broadcast routine

See also
next slide



2. Partitioning & Divide-And-Conquer Strategies

❖ **“all-to-all” broadcast routine**



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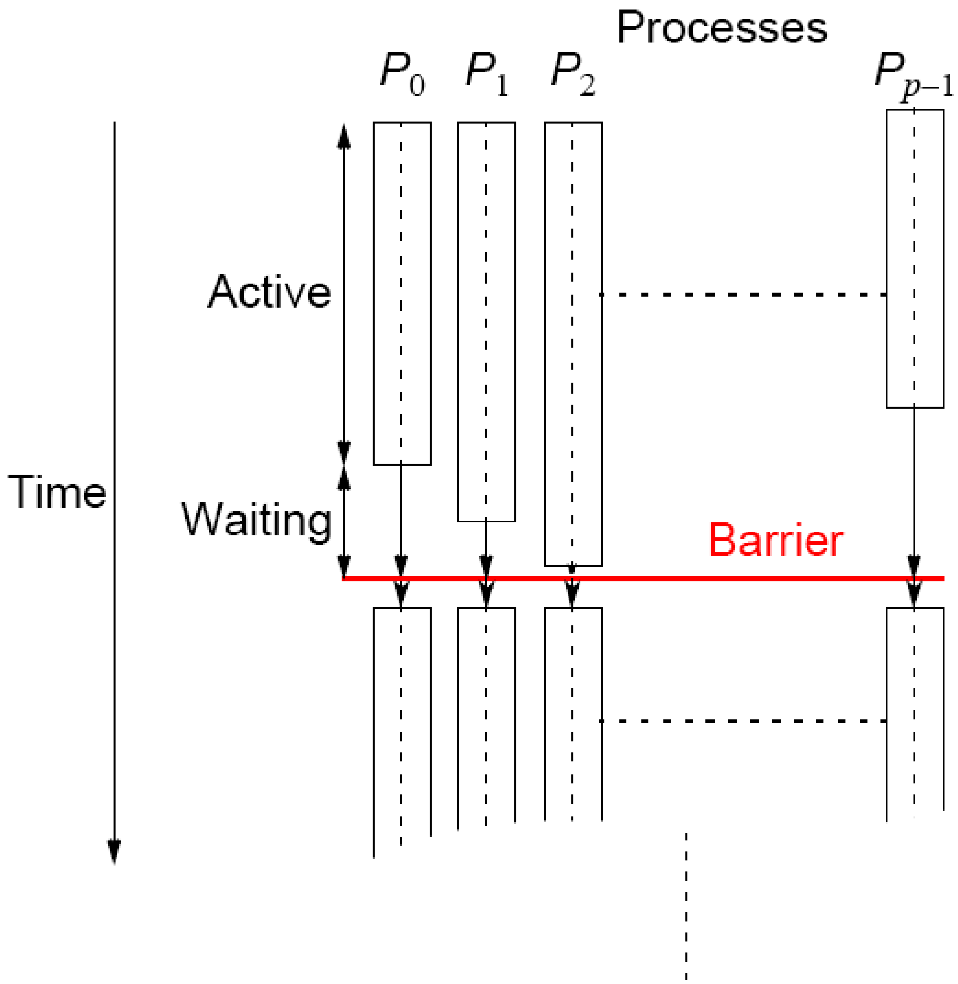
3. Synchronous Computation

- **In a (fully) synchronous application, all the processes synchronized at regular points.**
- **Barrier**
  - A basic mechanism for synchronizing processes - inserted at the point in each process where it must wait.
  - All processes can continue from this point when all the processes have reached it (or, in some implementations, when a stated number of processes have reached this point).

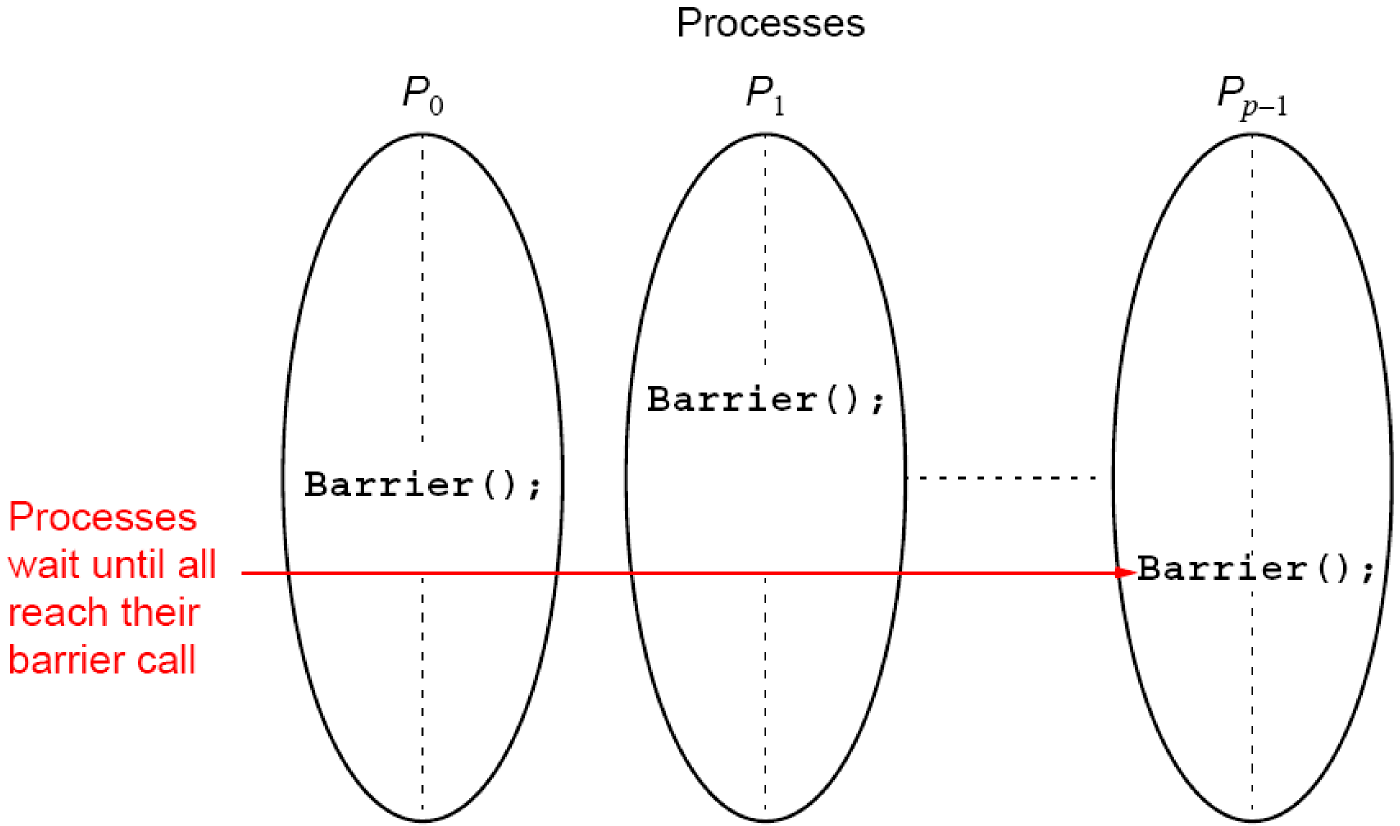
3. Synchronous Computation

❖ **Processes reaching barrier at different times**



3. Synchronous Computation

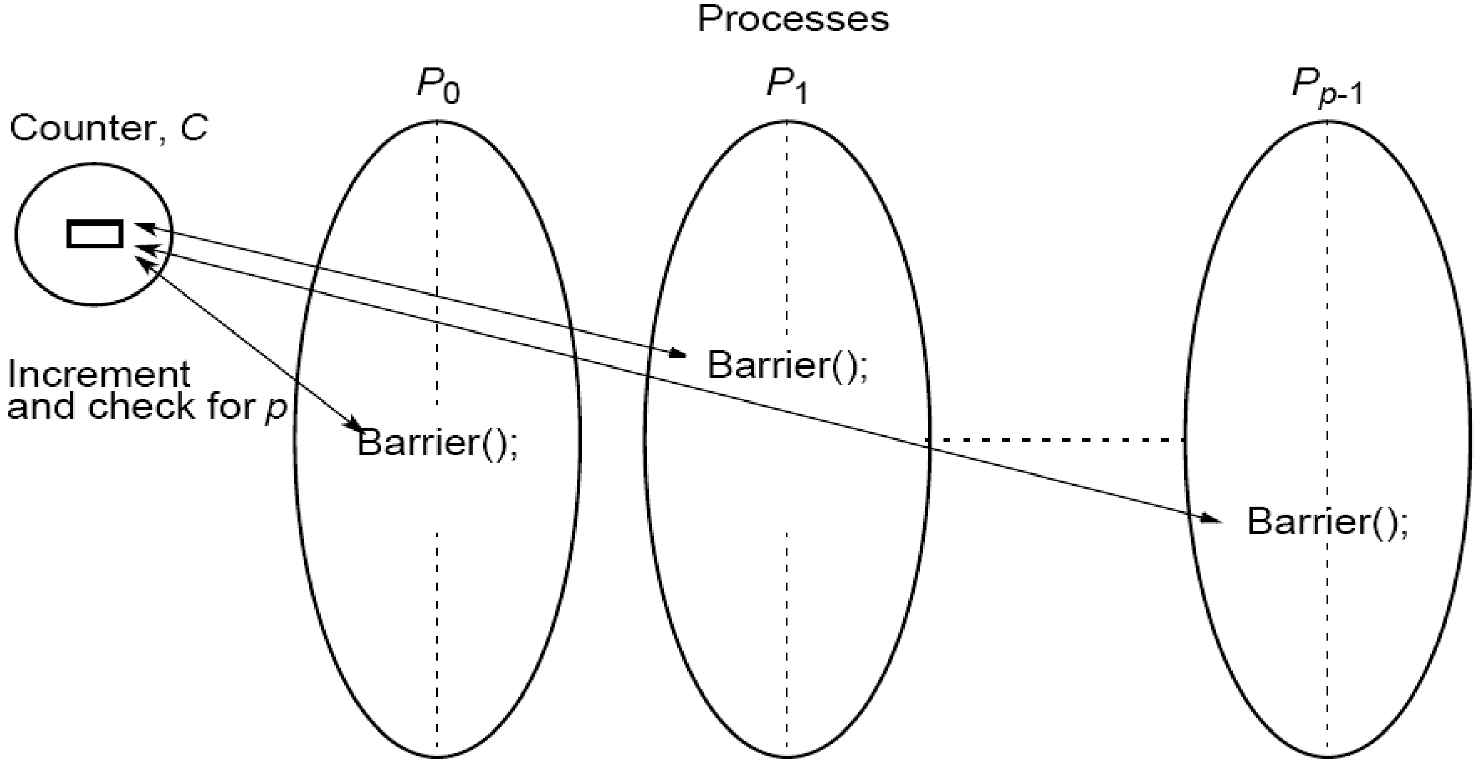
❖ **In message-passing systems, barriers provided with library routines:**



3. Synchronous Computation

❖ Barrier Implementation – Counter implementation

- a linear barrier



3. Synchronous Computation

❖ Barrier Implementation - Counter implementation

- Good barrier implementations must take into account that a barrier might be used more than once in a process.
- Might be possible for a process to enter the barrier for a second time before previous processes have left the barrier for the first time.

3. Synchronous Computation

❖ Barrier Implementation - Counter implementation

- Counter-based barriers often have two phases:
  - A process enters arrival phase and does not leave this phase until all processes have arrived in this phase.
  - Then processes move to departure phase and are released.

3. Synchronous Computation

❖ Barrier Implementation - Counter implementation

- Master:

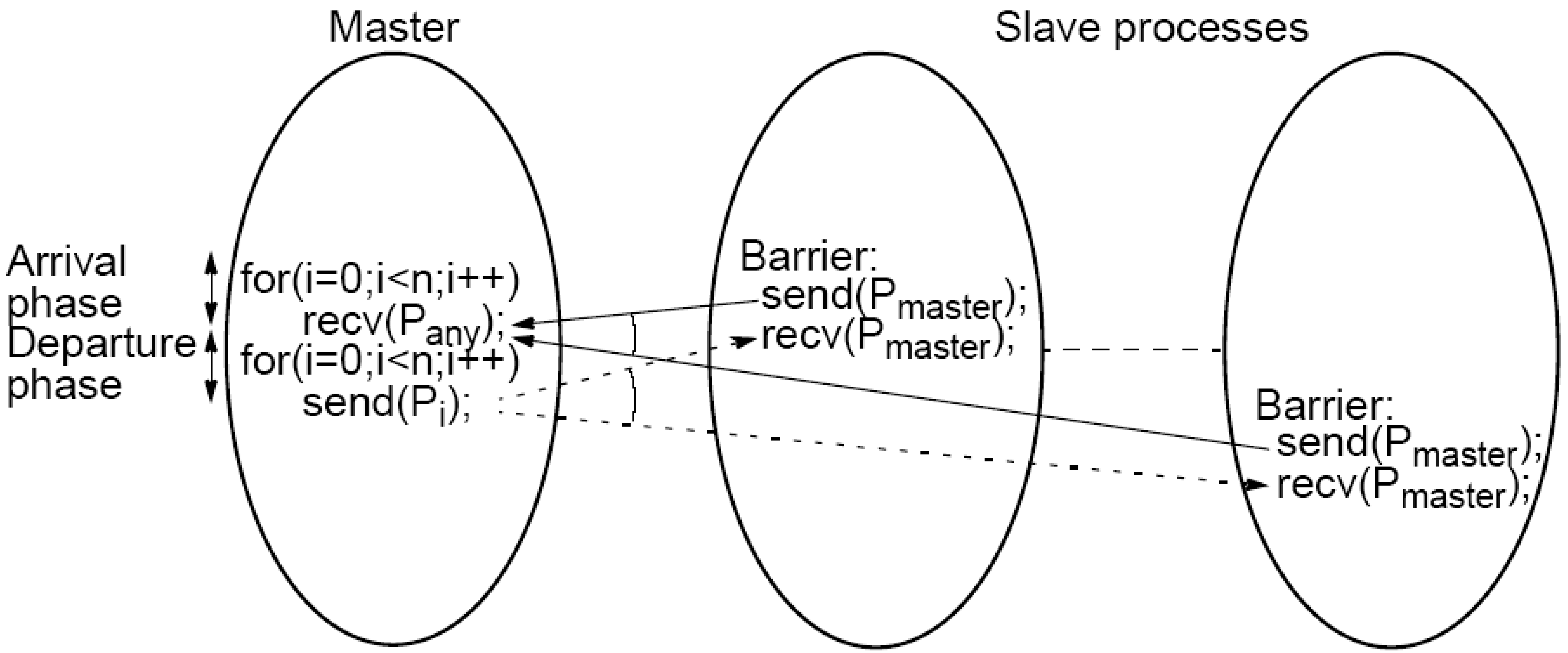
```
for (i = 0; i < n; i++)        /*count slaves as they reach barrier*/
        recv(Pany);
for (i = 0; i < n; i++)        /* release slaves */
        send(Pi);
```

- Slave processes:

```
send(Pmaster);
recv(Pmaster);
```

3. Synchronous Computation

❖ Barrier Implementation - Counter implementation



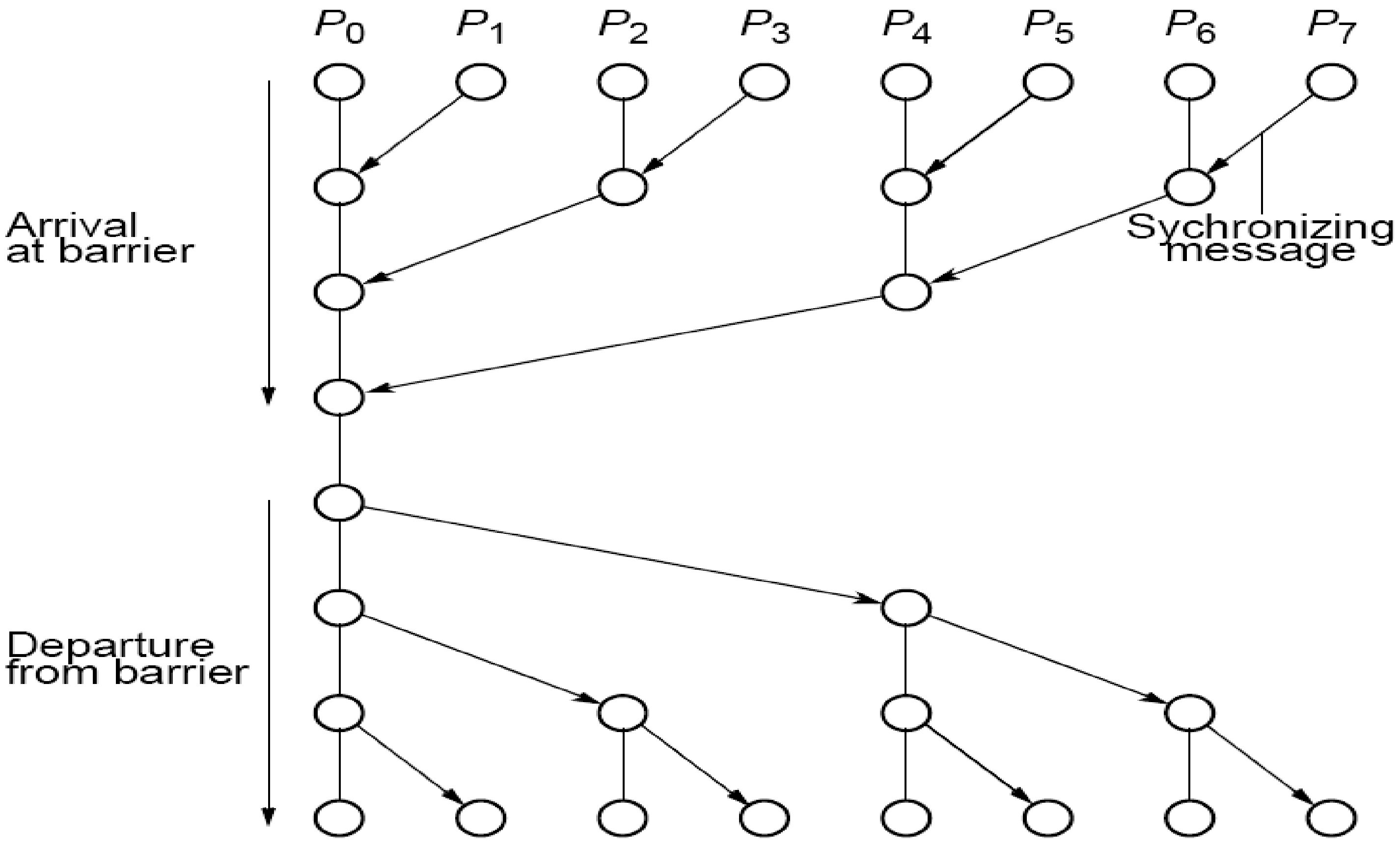
❖ Barrier Implementation - Tree implementation

- 1st stage: *P*1 sends message to *P*0; (when *P*1 reaches its barrier)
  *P*3 sends message to *P*2; (when *P*3 reaches its barrier)
  *P*5 sends message to *P*4; (when *P*5 reaches its barrier)
  *P*7 sends message to *P*6; (when *P*7 reaches its barrier)
- 2nd stage: *P*2 sends message to *P*0; (*P*2 & *P*3 reached their barrier)
  *P*6 sends message to *P*4; (*P*6 & *P*7 reached their barrier
- 3rd stage: *P*4 sends message to *P*0; (*P*4, *P*5, *P*6, & *P*7 reached barrier)
  *P*0 terminates arrival phase; (when *P*0 reaches barrier & received message from *P*4)

Release with a reverse tree construction.

3. Synchronous Computation

❖ Barrier Implementation - Tree implementation



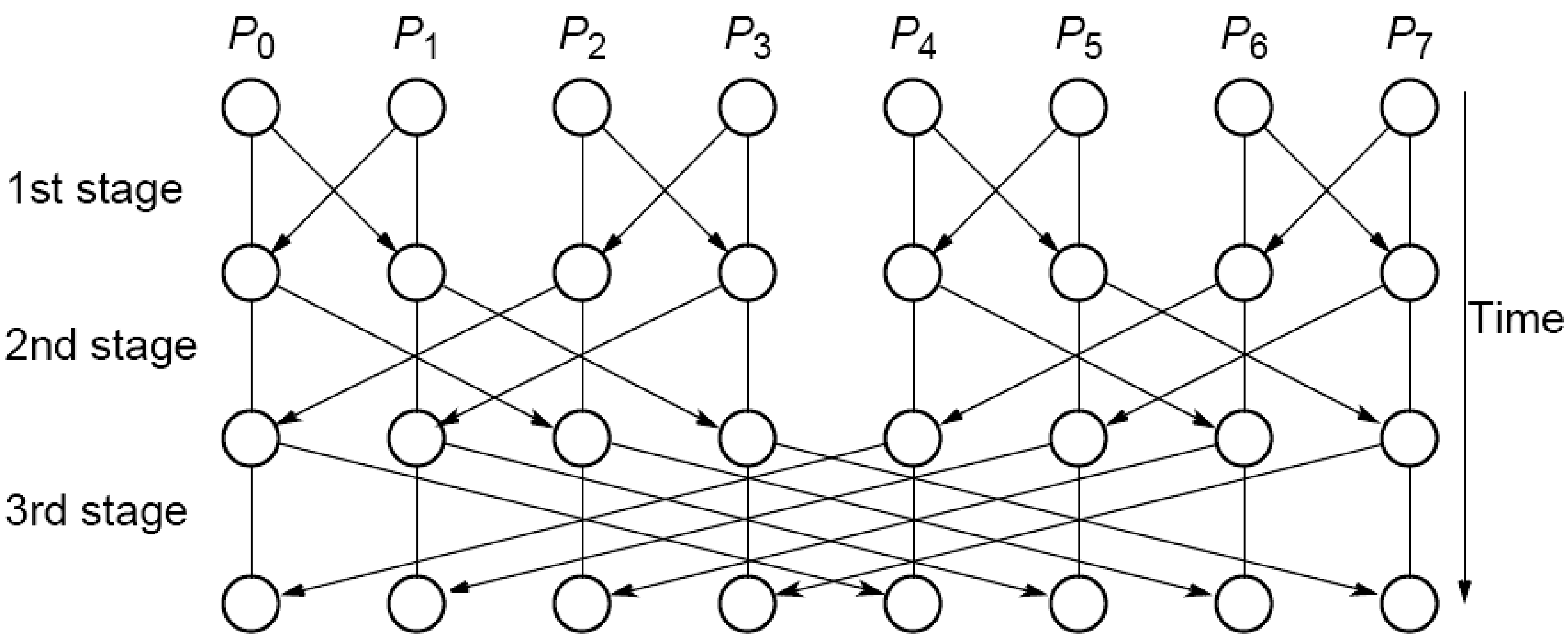
3. Synchronous Computation

❖ Barrier Implementation – Butterfly Barrier

1st stage $P_0 \leftrightarrow P_1, P_2 \leftrightarrow P_3, P_4 \leftrightarrow P_5, P_6 \leftrightarrow P_7$

2nd stage $P_0 \leftrightarrow P_2, P_1 \leftrightarrow P_3, P_4 \leftrightarrow P_6, P_5 \leftrightarrow P_7$

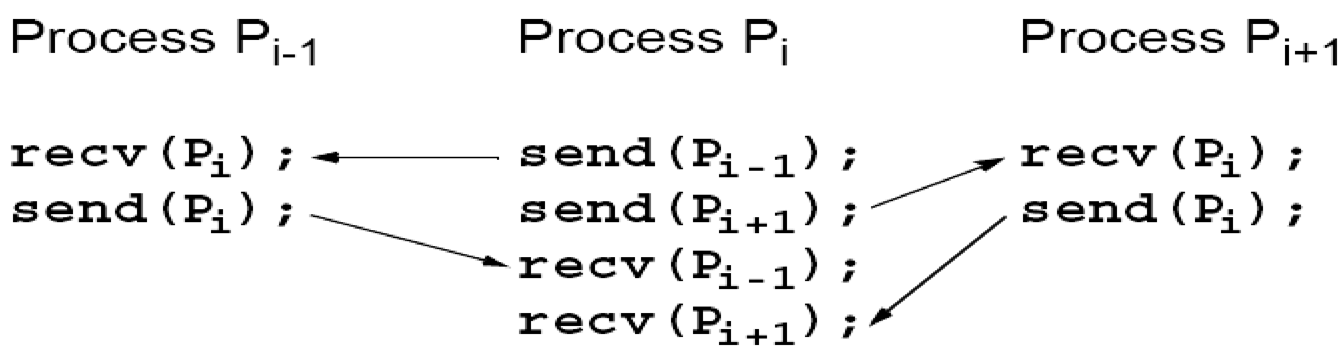
3rd stage $P_0 \leftrightarrow P_4, P_1 \leftrightarrow P_5, P_2 \leftrightarrow P_6, P_3 \leftrightarrow P_7$



3. Synchronous Computation

❖ Local Synchronization

- Suppose a process *Pi* needs to be synchronized and to exchange data with process *Pi*-1 and process *Pi*+1 before continuing:



- Not a perfect three-process barrier because process *Pi*-1 will only synchronize with *Pi* and continue as soon as *Pi* allows. Similarly, process *Pi*+1 only synchronizes with P*i*.

3. Synchronous Computation

❖ Deadlock

- When a pair of processes each send and receive from each other, deadlock may occur.
- Deadlock will occur if both processes perform the send, using synchronous routines first (or blocking routines without sufficient buffering). This is because neither will return; they will wait for matching receives that are never reached.

3. Synchronous Computation

❖ Deadlock – Solution

- Arrange for one process to receive first and then send and the other process to send first and then receive.
- Combined deadlock-free blocking sendrecv() routines

Example

Process P_{i-1}	Process P_i	Process P_{i+1}
sendrecv(P_i); ⟷	sendrecv(P_{i-1});	
	sendrecv(P_{i+1}); ⟷	sendrecv(P_i);

3. Synchronous Computation

❖ Synchronized Computations

- Can be classified as:
  - In fully synchronous, all processes involved in the computation must be synchronized.
  - In locally synchronous, processes only need to synchronize with a set of logically nearby processes, not all processes involved in the computation

3. Synchronous Computation

❖ Fully Synchronized Computation - Data Parallel Computations

- Same operation performed on different data elements simultaneously; i.e., in parallel.
- Particularly convenient because:
  - Ease of programming (essentially only one program).
  - Can scale easily to larger problem sizes.
  - Many numeric and some non-numeric problems can be cast in a data parallel form.

3. Synchronous Computation

❖ Fully Synchronized Computation - Data Parallel Computations

- To add the same constant to each element of an array:

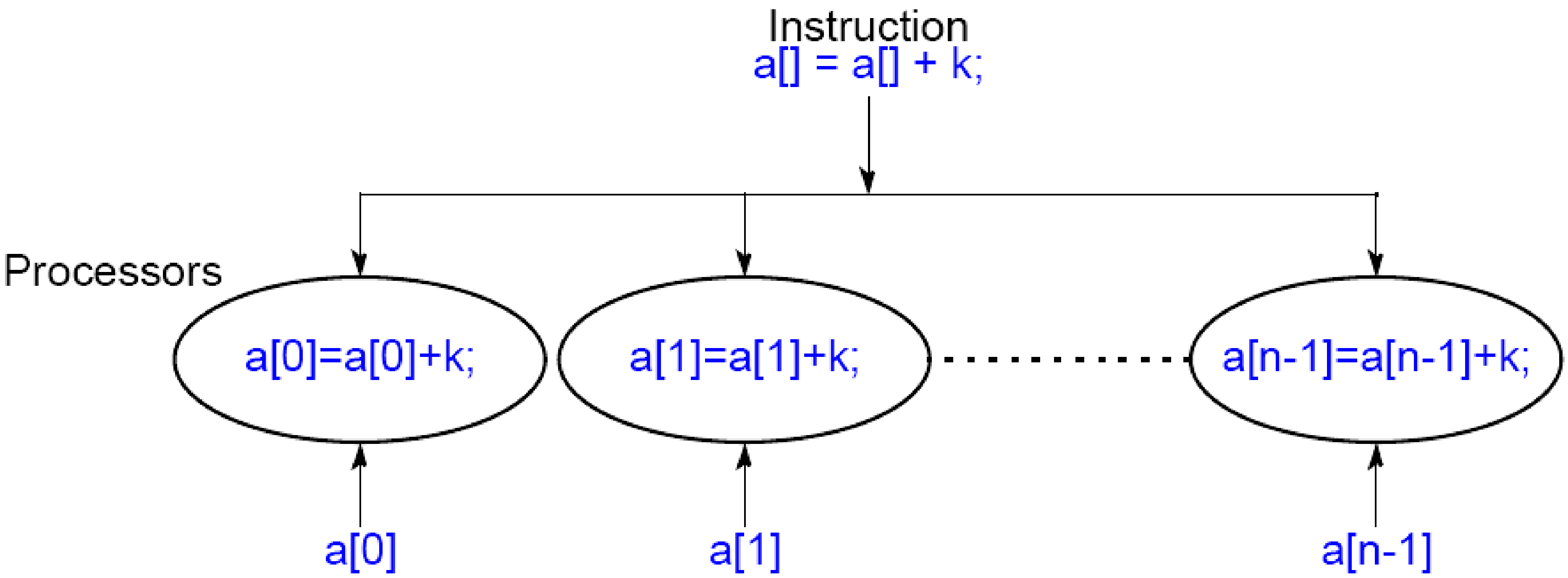
```
for (i = 0; i < n; i++)
        a[i] = a[i] + k;
```

- The statement: **a[i] = a[i] + k;**

could be executed simultaneously by multiple processors, each using a different index **i (0 < i <= n)**.

3. Synchronous Computation

❖ **Fully Synchronized Computation - Data Parallel Computations**



3. Synchronous Computation

❖ Fully Synchronized Computation - Data Parallel Computations

- **forall construct:** special "parallel" construct in parallel programming languages to specify data parallel operations

```
forall (i = 0; i < n; i++) {
        body
}
```

- states that *n* instances of the statements of the body can be executed simultaneously.

3. Synchronous Computation

❖ Fully Synchronized Computation - Data Parallel Computations

- To add **k** to each element of an array, **a**, we can write

```
forall (i = 0; i < n; i++)
        a[i] = a[i] + k;
```

- Data parallel technique applied to multiprocessors and multicomputers

```
i = myrank;
a[i] = a[i] + k;        /* body */
barrier(mygroup);
```

3. Synchronous Computation

❖ **Fully Synchronized Computation - Synchronous Iteration**

- Each iteration composed of several processes that start together at beginning of iteration. Next iteration cannot begin until all processes have finished previous iteration.

3. Synchronous Computation

❖ Fully Synchronized Computation - Synchronous Iteration

- Using **forall** construct:

```
for (j = 0; j < n; j++)            /*for each synch. iteration */
        forall (i = 0; i < N; i++)    /*N procs each using*/
                body(i);              /* specific value of i */
```

- Using message passing barrier:

```
for (j = 0; j < n; j++) {          /*for each synchr.iteration */
        i = myrank;                /*find value of i to be used */
        body(i);
        barrier(mygroup);
}
```

3. Synchronous Computation

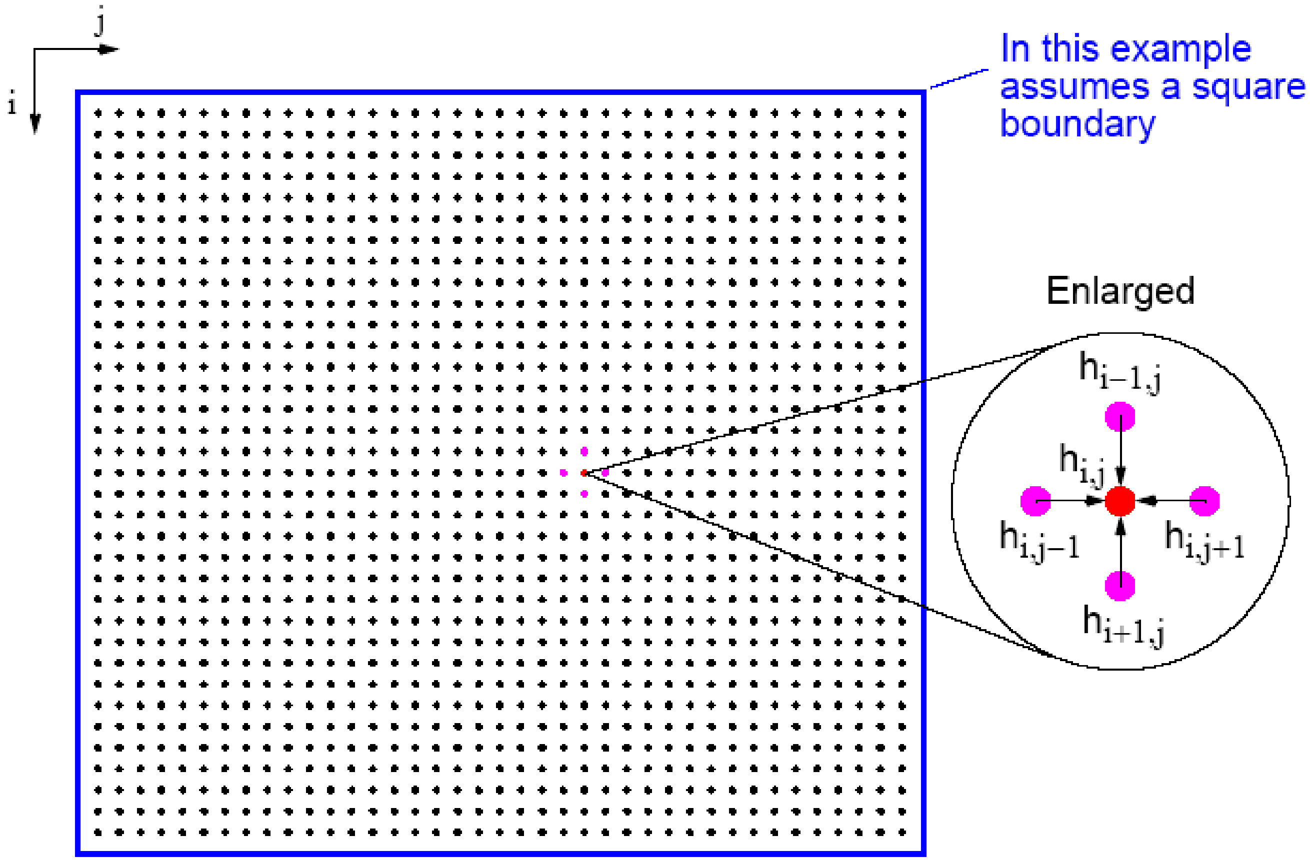
❖ Fully Synchronized Computation - Synchronous Iteration

- Solving a General System of Linear Equations by Iteration

$$
\begin{array}{lll}
a_{n-1,0}x_0 + a_{n-1,1}x_1 + a_{n-1,2}x_2 \ldots & + a_{n-1,n-1}x_{n-1} & = b_{n-1} \\
\quad\quad . & & \\
\quad\quad . & & \\
\quad\quad . & & \\
a_{2,0}x_0 + a_{2,1}x_1 + a_{2,2}x_2 \ldots & + a_{2,n-1}x_{n-1} & = b_2 \\
a_{1,0}x_0 + a_{1,1}x_1 + a_{1,2}x_2 \ldots & + a_{1,n-1}x_{n-1} & = b_1 \\
a_{0,0}x_0 + a_{0,1}x_1 + a_{0,2}x_2 \ldots & + a_{0,n-1}x_{n-1} & = b_0
\end{array}
$$

3. Synchronous Computation

❖ **Locally Synchronized Computation - Heat Distribution Problem**



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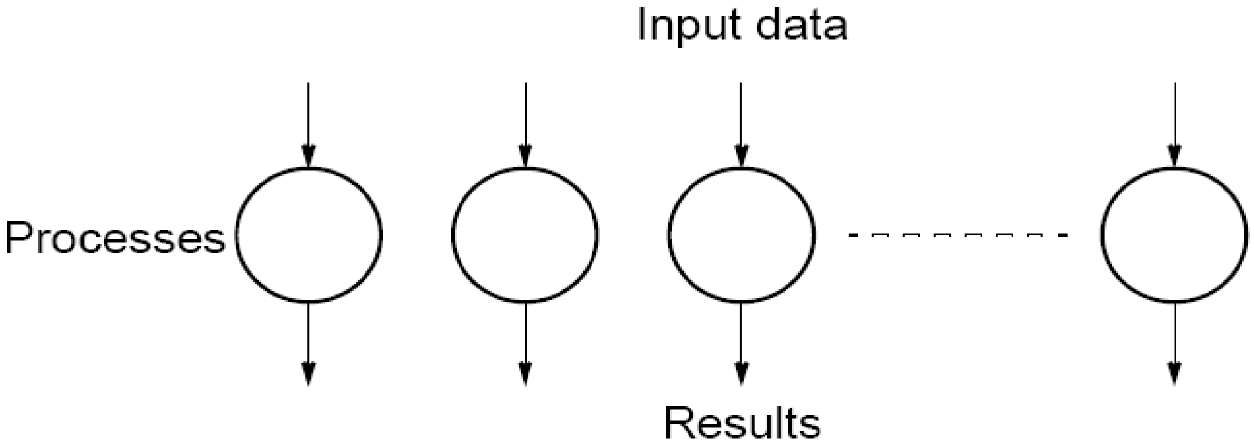
4. Embarrassingly Parallel Computations

A computation that can obviously be divided into a number of completely independent parts, each of which can be executed by a separate process(or).

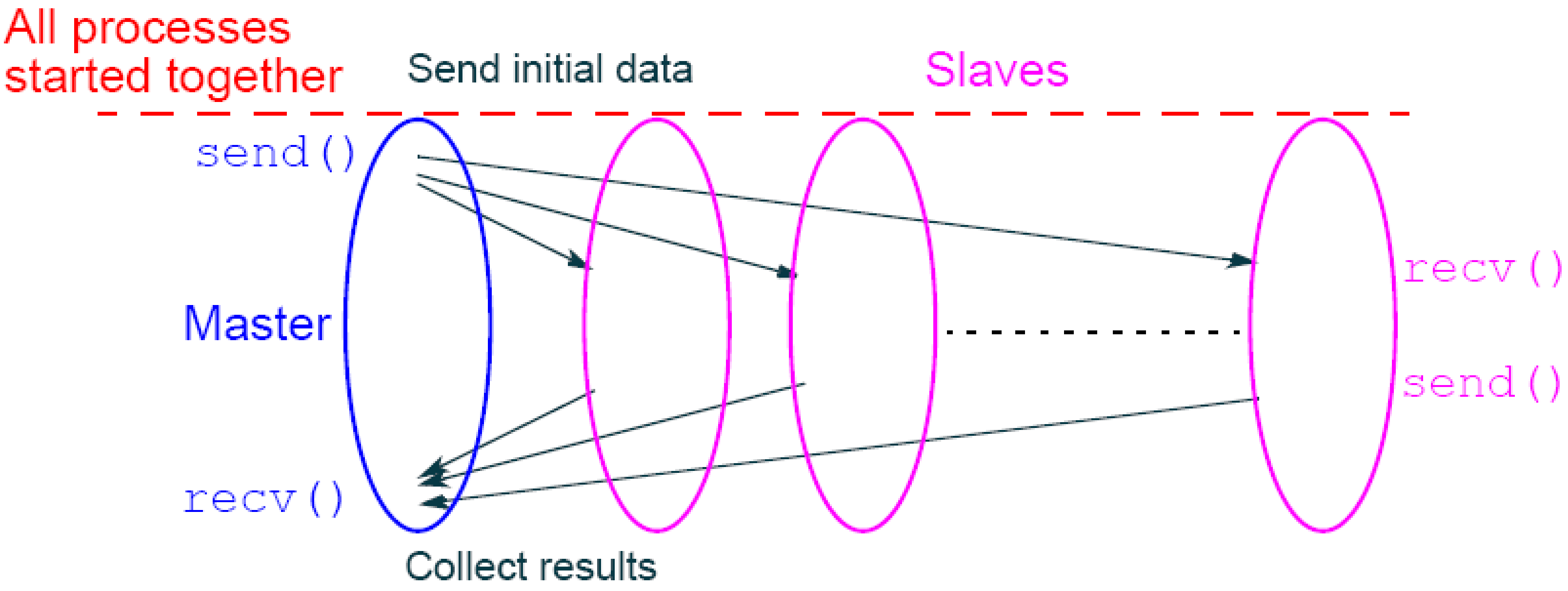


No communication or very little communication between processes

Each process can do its tasks without any interaction with other processes

4. Embarrassingly Parallel Computations

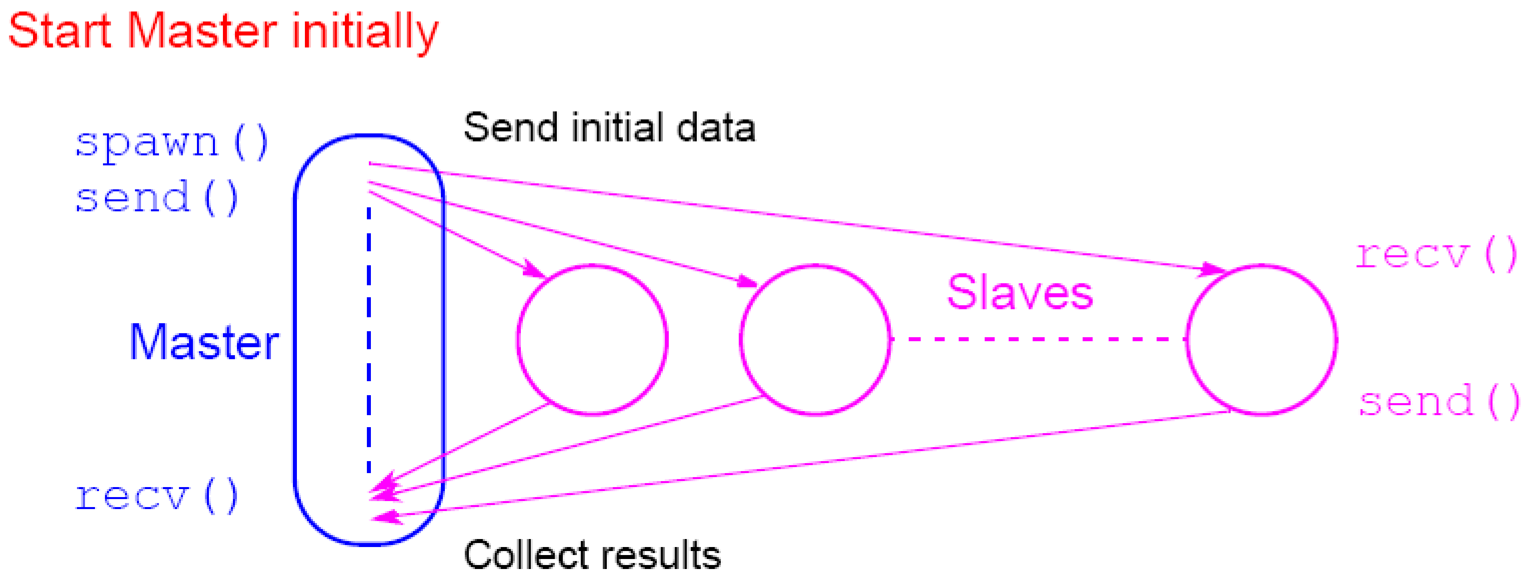
- **static process creation and master-slave approach**



Usual MPI approach

4. Embarrassingly Parallel Computations

❖ **dynamic process creation and master-slave approach**



(PVM approach)

Mandelbrot Set

Set of points in a complex plane that are quasi-stable (will increase and decrease, but not exceed some limit) when computed by iterating the function

$$z_{k+1} = z_k^2 + c$$

where z_{k+1} is the $(k + 1)th$ iteration of the complex number $z = a + bi$ and c is a complex number giving position of point in the complex plane. The initial value for z is zero.

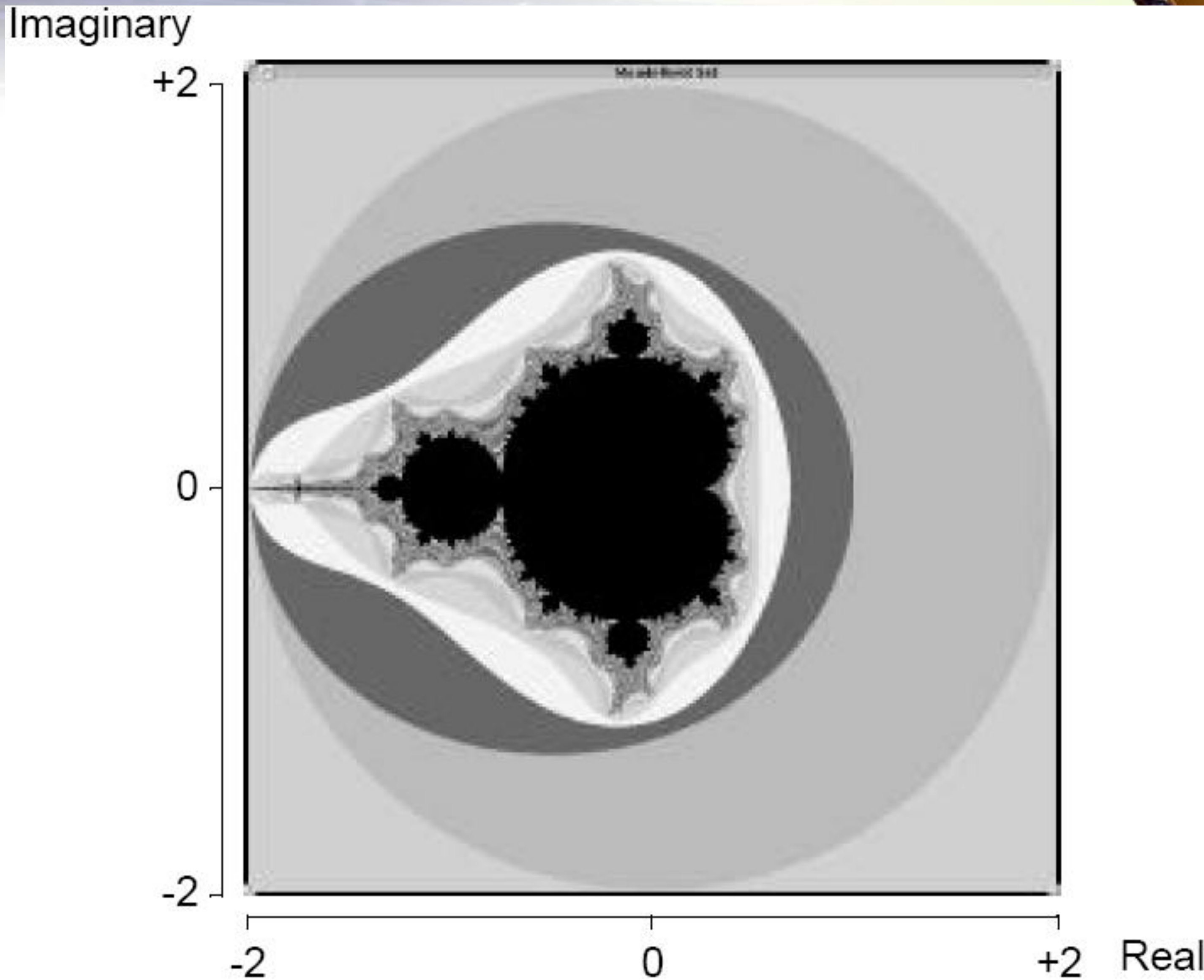
Iterations continued until magnitude of z is greater than 2 or number of iterations reaches arbitrary limit. Magnitude of z is the length of the vector given by

$$z_{length} = \sqrt{a^2 + b^2}$$

Sequential routine computing value of one point returning number of iterations

```
structure complex {
        float real;
        float imag;
};
int cal_pixel(complex c)
{
        int count, max;
        complex z;
        float temp, lengthsq;
        max = 256;
        z.real = 0; z.imag = 0;
        count = 0;                      /* number of iterations */
        do {
                temp = z.real * z.real - z.imag * z.imag + c.real;
                z.imag = 2 * z.real * z.imag + c.imag;
                z.real = temp;
                lengthsq = z.real * z.real + z.imag * z.imag;
                count++;
        } while ((lengthsq < 4.0) && (count < max));
        return count;
}
```

Mandelbrot set



Parallelizing Mandelbrot Set Computation

Static Task Assignment

Simply divide the region in to fixed number of parts, each computed by a separate processor.

Not very successful because different regions require different numbers of iterations and time.

Dynamic Task Assignment

Have processor request regions after computing previous regions

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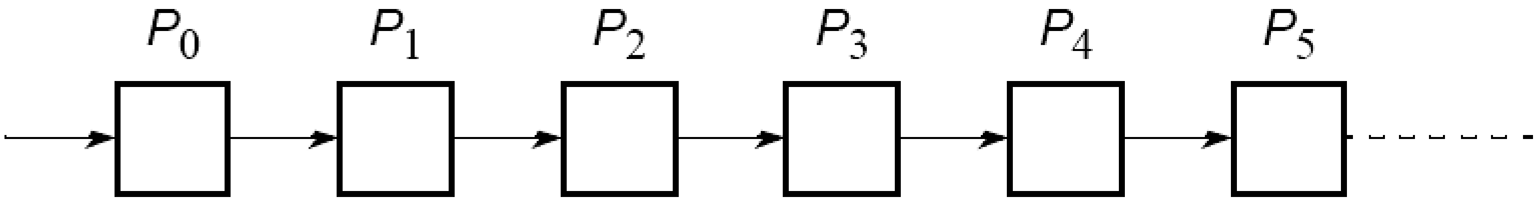
5. Pipelined Computations

- Problem divided into a series of tasks that have to be completed one after the other (the basis of sequential programming). Each task executed by a separate process or processor.



5. Pipelined Computations

1. If more than one instance of the complete problem is to be executed
2. If a series of data items must be processed, each requiring multiple operations
3. If information to start next process can be passed forward before process has completed all its internal operations

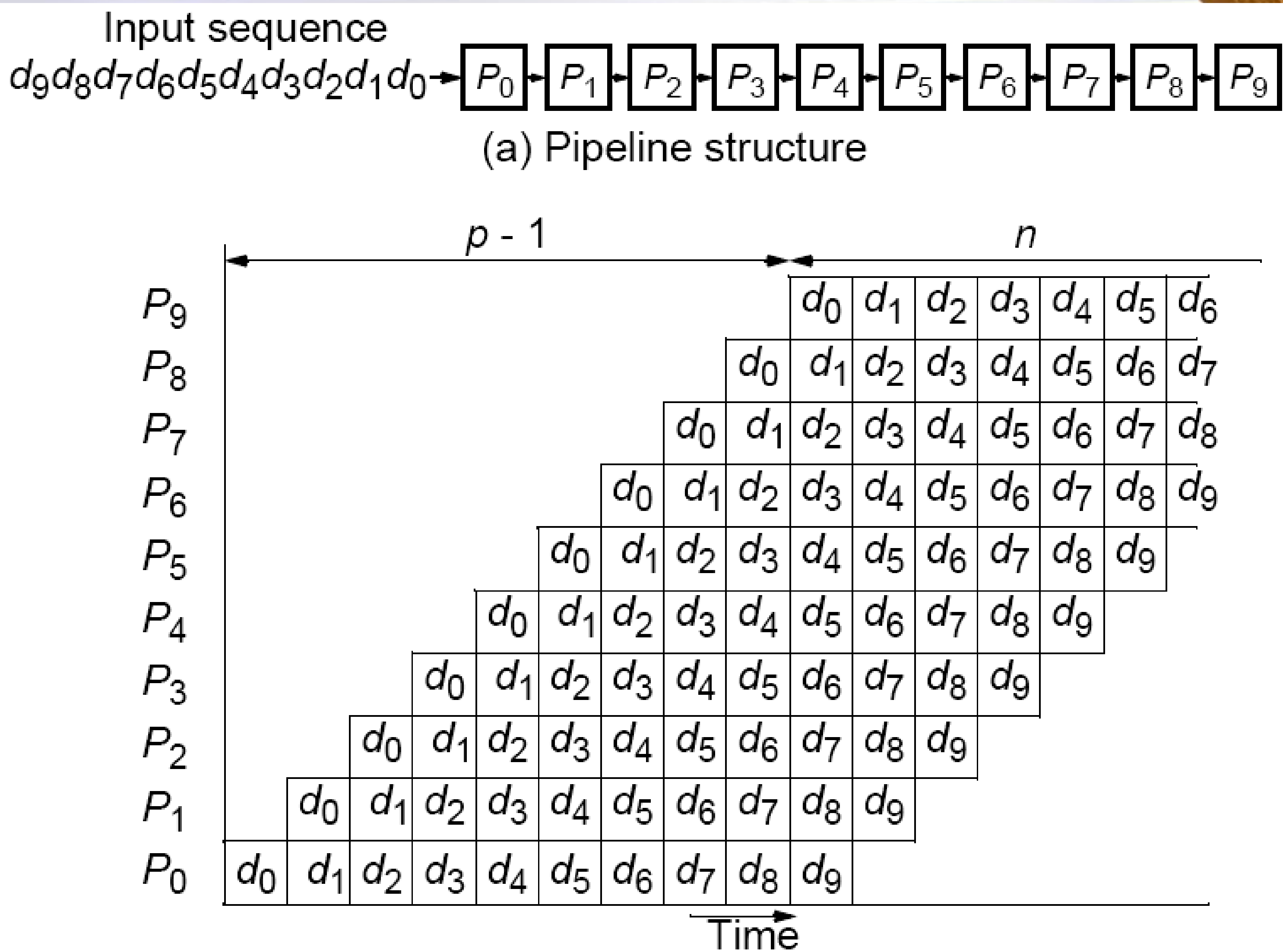
"Type 1" Pipeline Space-Time Diagram

$p - 1$ ⟷ m

P_5						Instance 1	Instance 2	Instance 3	Instance 4	Instance 5	
P_4					Instance 1	Instance 2	Instance 3	Instance 4	Instance 5	Instance 6	
P_3				Instance 1	Instance 2	Instance 3	Instance 4	Instance 5	Instance 6	Instance 7	
P_2			Instance 1	Instance 2	Instance 3	Instance 4	Instance 5	Instance 6	Instance 7		
P_1		Instance 1	Instance 2	Instance 3	Instance 4	Instance 5	Instance 6	Instance 7			
P_0	Instance 1	Instance 2	Instance 3	Instance 4	Instance 5	Instance 6	Instance 7				

Time →

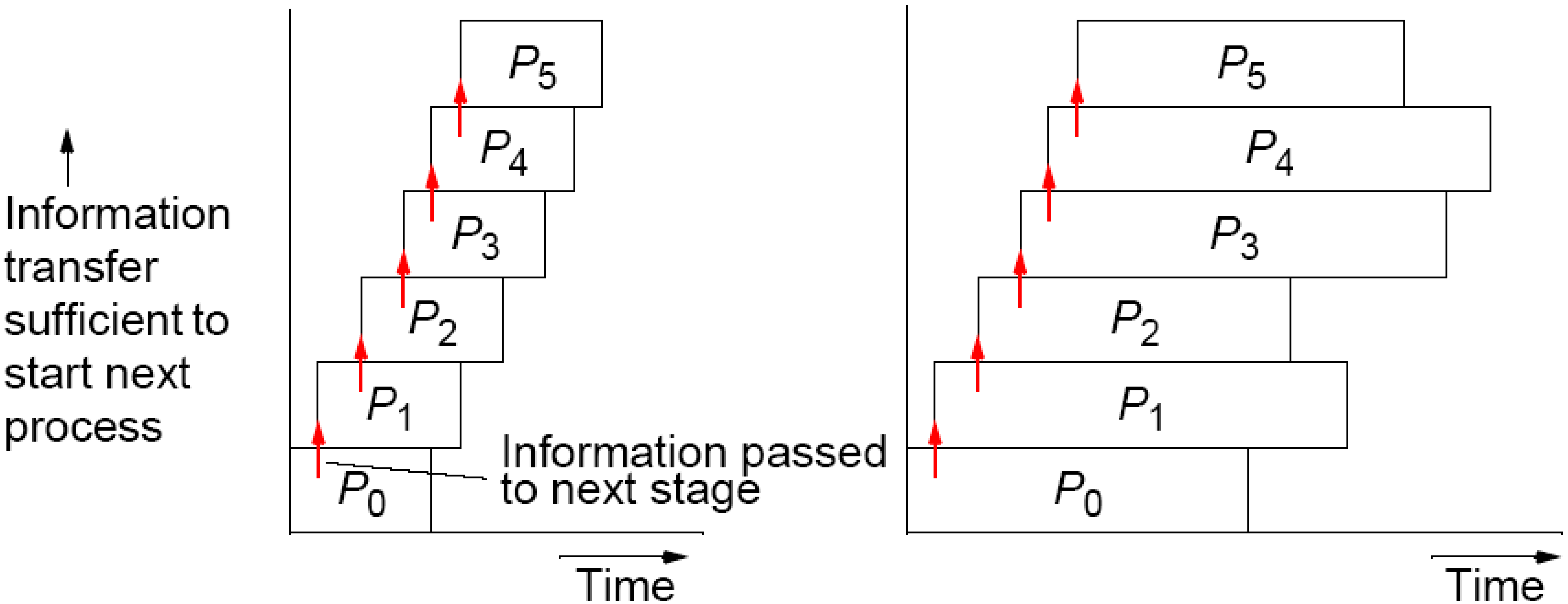
"Type 2" Pipeline Space-Time Diagram



(a) Pipeline structure

(b) Timing diagram

“Type 3” Pipeline Space-Time Diagram



(a) Processes with the same execution time

(b) Processes not with the same execution time

Solving a System of Linear Equations
Upper-triangular form

$$a_{n-1,0}x_0 + a_{n-1,1}x_1 + a_{n-1,2}x_2 \quad \ldots \quad + a_{n-1,n-1}x_{n-1} = b_{n-1}$$

.

.

$$a_{2,0}x_0 + a_{2,1}x_1 + a_{2,2}x_2 = b_2$$

$$a_{1,0}x_0 + a_{1,1}x_1 = b_1$$

$$a_{0,0}x_0 = b_0$$

where *a's* and *b's* are constants and *x*'s are unknowns to be found.

Back Substitution

First, unknown x_0 is found from last equation; i.e.,

$$x_0 = \frac{b_0}{a_{0,0}}$$

Value obtained for x_0 substituted into next equation to obtain x_1; i.e.,

$$x_1 = \frac{b_1 - a_{1,0}x_0}{a_{1,1}}$$

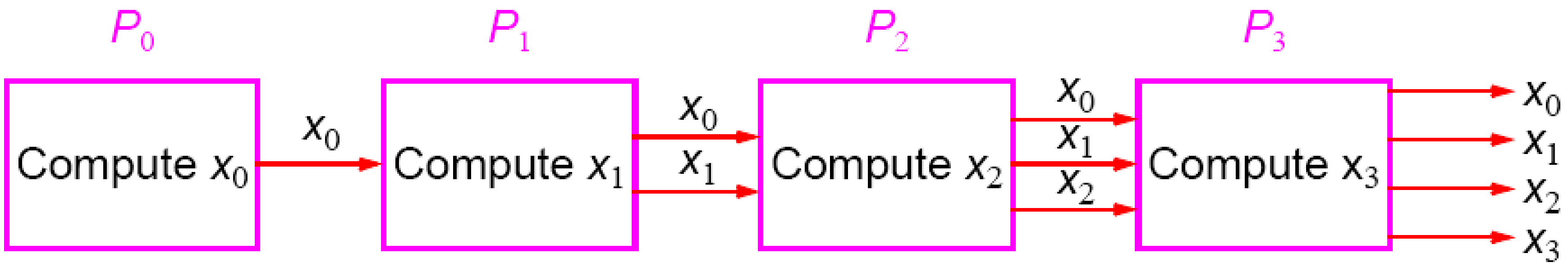
Values obtained for x_1 and x_0 substituted into next equation to obtain x_2:

$$x_2 = \frac{b_2 - a_{2,0}x_0 - a_{2,1}x_1}{a_{2,2}}$$

and so on until all the unknowns are found.

Pipeline Solution

First pipeline stage computes x_0 and passes x_0 onto the second stage, which computes x_1 from x_0 and passes both x_0 and x_1 onto the next stage, which computes x_2 from x_0 and x_1, and so on.



Type 3 pipeline computation

The ith process ($0 < i < n$) receives the values $x_0, x_1, x_2, \ldots, x_{i-1}$ and computes x_i from the equation:

$$x_i = \frac{b_i - \sum_{j=0}^{i-1} a_{i,j} x_j}{a_{i,i}}$$

Sequential Code

Given constants $a_{i,j}$ and b_k stored in arrays **a[ ][ ]** and **b[ ]**, respectively, and values for unknowns to be stored in array, **x[ ]**, sequential code could be

```
x[0] = b[0]/a[0][0];              //computed separately
for (i = 1; i < n; i++) {          /*for remaining unknowns*/
        sum = 0;
        For (j = 0; j < i; j++
                sum = sum + a[i][j]*x[j];
        x[i] = (b[i] - sum)/a[i][i];
}
```

Pipelined Solution of A Set of Upper-Triangular Linear Equations

Parallel Code:

- The pseudo code of process P_i (1<i<n) of the pipelined version could be:

1 < i < p = n

```
for (j = 0; j< i; j++) {
        recv(P i-1, x[j]);          // Receive x0, x1,.. from P(i-1)
        send(P i+1,x[j];            // Send x0, x1,.. from P(i-1)
        sum = sum + a[i][j]*x[j];   //Compute sum term
}
sum = 0;
x[i] = (b[i] - sum)/a[i][i];        // Compute xi
send(Pi+1, x[j]);                   // Send xi to P(i+1)
}
```

Contents

1 Message-Passing Computing

2 Partitioning & Divide-And-Conquer Strategies

3 Synchronous Computation

4 Embarrassingly Parallel Computations

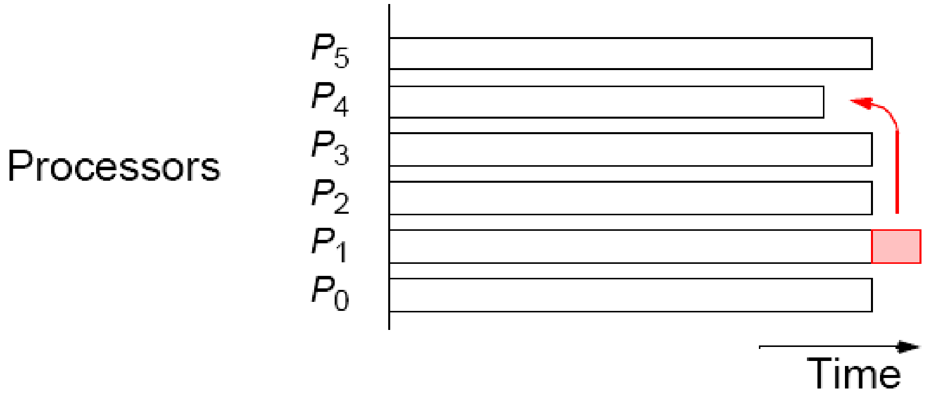
5 Pipelined Computations

6 Load Balancing & Termination Detection

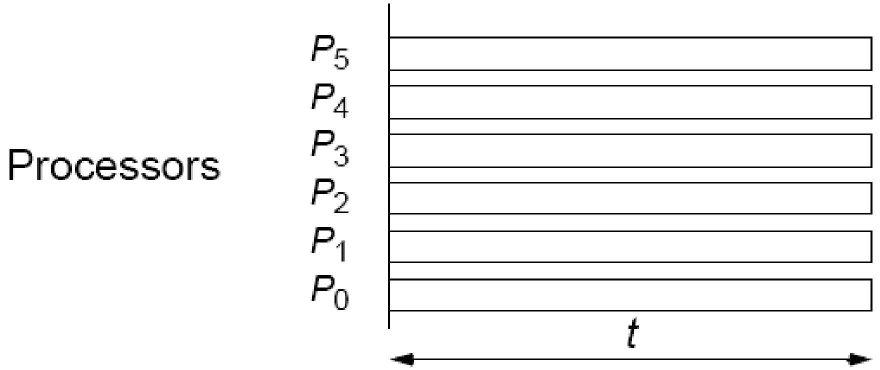
6. Load Balancing & Termination Detection

- *Load balancing* – used to distribute computations fairly across processors in order to obtain the highest possible execution speed.
- *Termination detection* – detecting when a computation has been completed. More difficult when the computation is distributed.

Load Balancing



(a) Imperfect load balancing leading to increased execution time



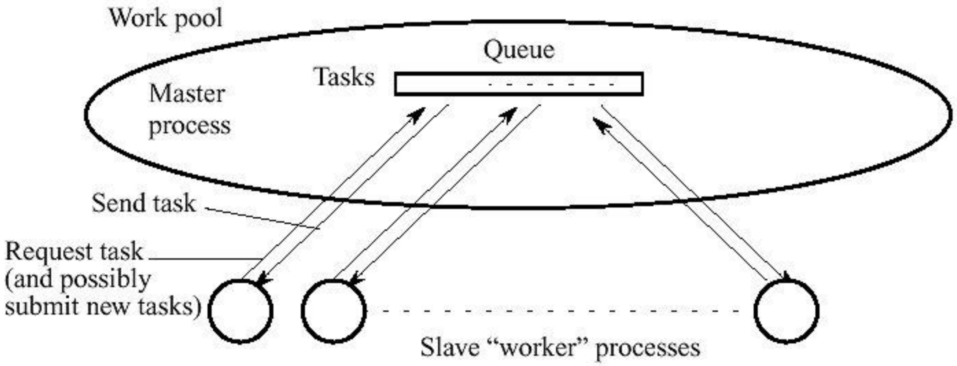
(b) Perfect load balancing

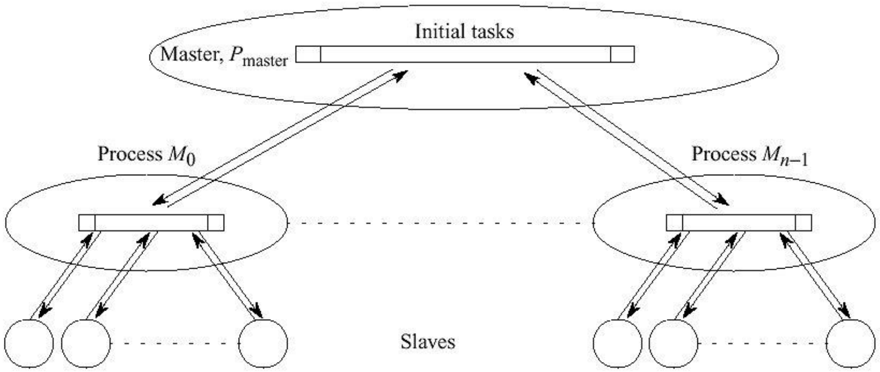
Static Load Balancing

- *Round robin algorithm* — passes out tasks in sequential order of processes coming back to the first when all processes have been given a task
- *Randomized algorithms* — selects processes at random to take tasks
- *Recursive bisection* — recursively divides the problem into sub-problems of equal computational effort while minimizing message passing
- *Simulated annealing* — an optimization technique
- *Genetic algorithm* — another optimization technique

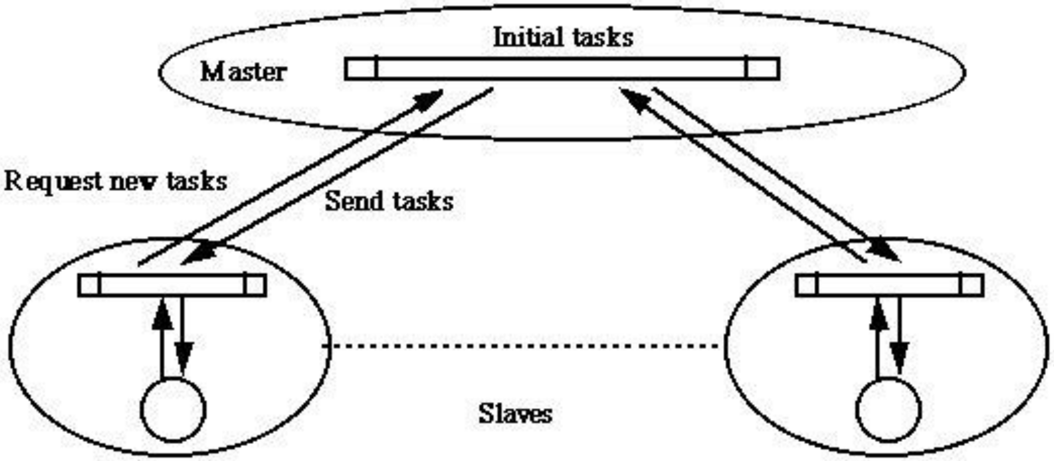
Dynamic Load Balancing

- Centralized dynamic load balancing
- Decentralized dynamic load balancing



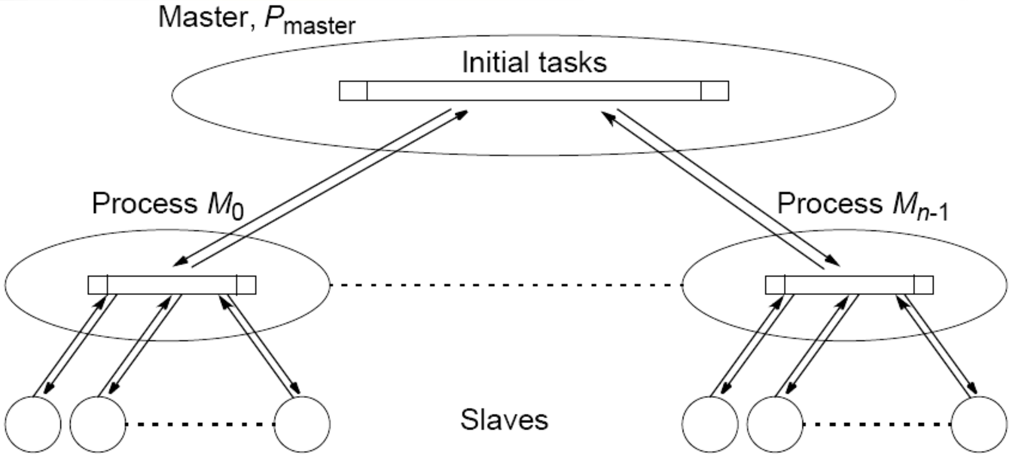


Centralized dynamic load balancing



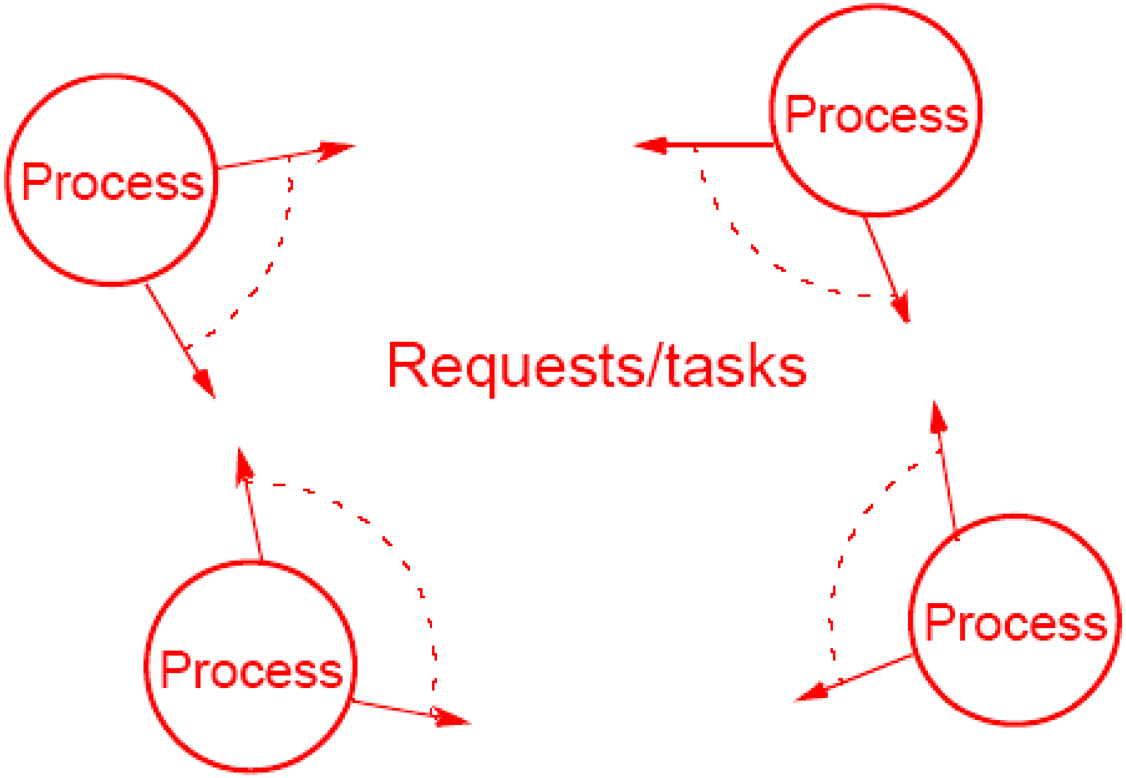
- ❖ *Advantage:The master process terminates the computation when*
  - *The task queue is empty, and*
  - *Every process has made a request for more tasks without any new tasks been generated.*
- ❖ *Disadvantages:*
  - *High task queue management overheads/load on master process.*
  - *Contention over access to single queue may lead to excessive contention delays.*

Decentralized Dynamic Load Balancing

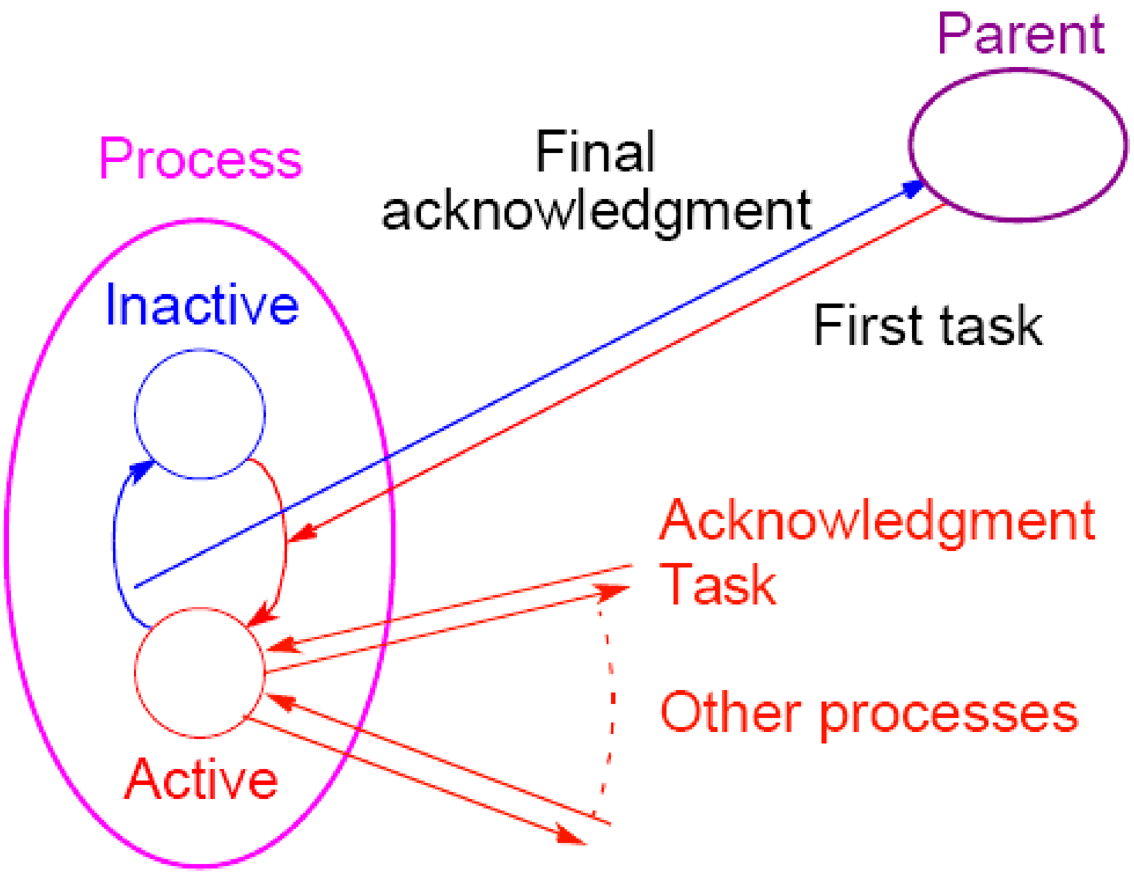


❖ *Tasks could be transferred by one of two methods:*
- *Receiver-initiated method.*
- *Sender-initiated method.*

Fully Distributed Work Pool

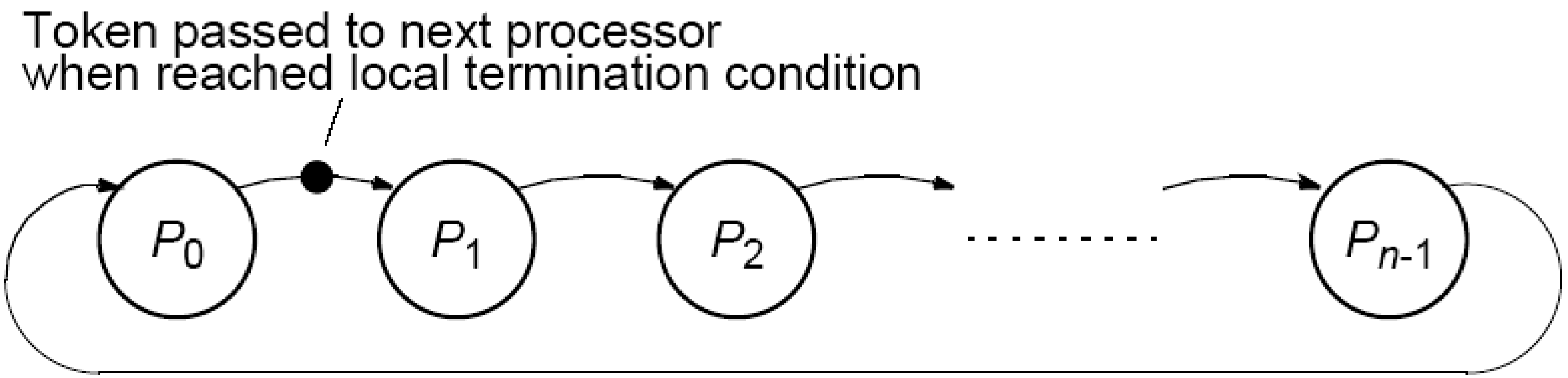


Termination Detection for Decentralized Dynamic Load Balancing



Message passing

Termination Detection for Decentralized Dynamic Load Balancing

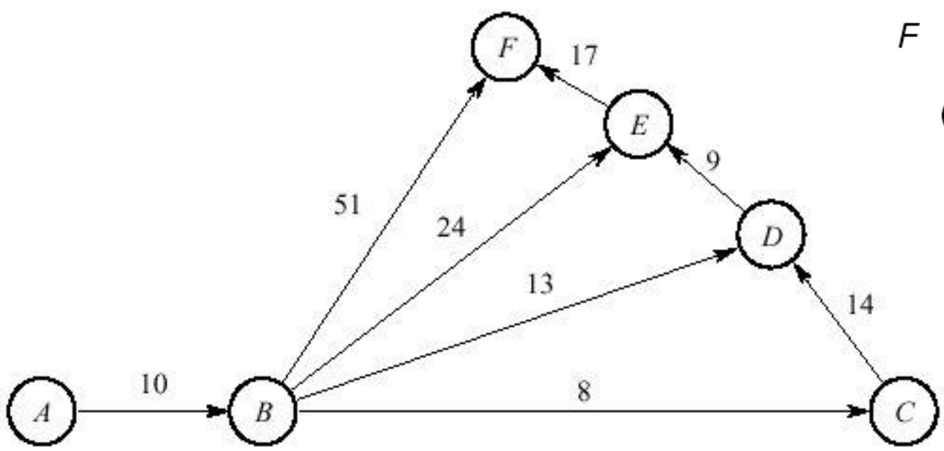


Ring termination detection algorithm

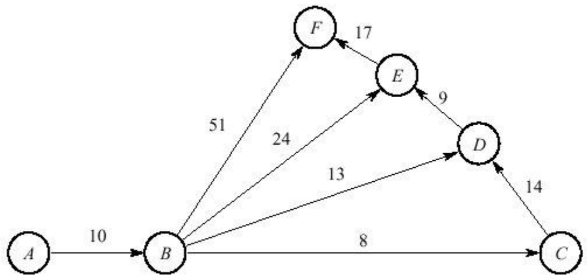
Program Example: Shortest Path Algorithm

Source \ Destination	A	B	C	D	E	F
A	•	10	•	•	•	•
B	•	•	8	13	24	51
C	•	•	•	14	•	•
D	•	•	•	•	9	•
E	•	•	•	•	•	17
F	•	•	•	•	•	•

(a) Adjacency matrix



Stages in Searching a Graph



Vertices to consider

A					

vertex_queue

Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	•	•	•	•	•

dist[]

After examining *A* to

Vertices to consider

B					

←

vertex_queue

Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	10	•	•	•	•

dist[]

After examining *B* to *F*, *E*, *D*, and *C*

Vertices to consider

E	*D*	*C*			

←

vertex_queue

Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	10	18	23	34	61

dist[]

After examining *D* to *E*:

Vertices to consider

C	*E*				

←

vertex_queue

Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	10	18	23	32	50

dist[]

Moore's Single-source Shortest-path Algorithm

Sequential Code:

```
while ((i=next_vertex())!=no_vertex)
    while (j=next_edge(vertex)!=no_edge)
        newdist_j=dist[i] + w[i][j];
        if (newdist_j < dist[j]) {
            dist[j]=newdist_j;
            append_gueue(j); }
    }
```

Parallel Implementation using Centralized Work Pool

Master

```
recv(any, Pi); /* request for task from process Pi */
if ((i= next_edge()!= no_edge)
    send(Pi, i, dist[i]);  /* send next vertex, and
        .                  /* current distance to vertex
recv(Pj, j, dist[j]);      /* receive new distances */
append_gueue(j);           /* append vertex to queue */
```

Parallel Implementation using Centralized Work Pool

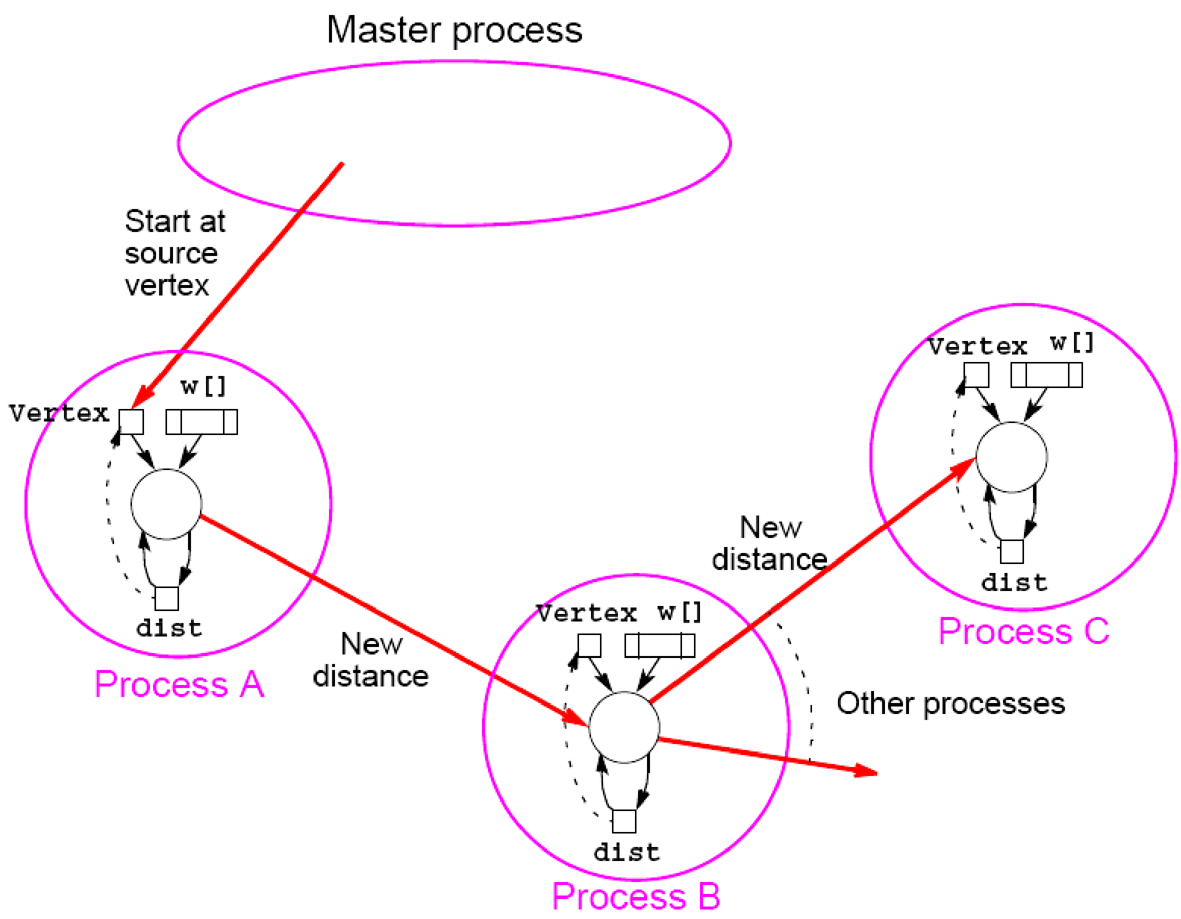
Slave (process i)

```
send(P_master, P_i); /* send a request for task */
recv(P_master, i, d); /* get vertex number and distance */
while (j=next_edge(vertex)!= no_edge) {  /* get next link
   around vertex */
     newdist_j = d + w[i][j];
     if (newdist_j < dist[j]) {
         dist[j]=newdist_j;
         send(P_master, j, dist[j]); /* send back updated
   distance */
     }
} /* no more vertices to consider */
```

i.e task

Done

Parallel Implementation
Using Decentralized Work Pool



Parallel Implementation Using Decentralized Work Pool

Master

```
if ((i = next_vertex()!= no_vertex)
    send(Pi, "start");  /* start up slave process i */
```

Slave (process i)

```
if (recv(Pj, msgtag = 1))   /* asking for distance */
    send(Pj, msgtag = 2, dist[i]); /* sending current
  distance */
if (nrecv(Pmaster) {      /* if start-up message */
    while (j=next_edge(vertex)!=no_edge) {      /* get next
  link around vertex */
        newdist_j = dist[i] + w[j];
        send(Pj, msgtag=1); /* Give me the distance */
        recv(Pi, msgtag = 2 , dist[j]);  * Thank you */
        if (newdist_j > dist[j]) {
            dist[j] = newdist_j;
            send(Pj, msgtag=3, dist[j]); * send updated
  distance to proc. j */
        }
    }
}
```

References

- *Parallel Programming: Techniques and Application Using Networked Workstations and Parallel Computers*, Barry Wilkinson and Michael Allen, Second Edition, Prentice Hall, 2005
- Using some slides of B. Wilkinson & M. Allen at http://coitweb.uncc.edu/~abw/parallel/par_prog/resources.htm

Thank You !