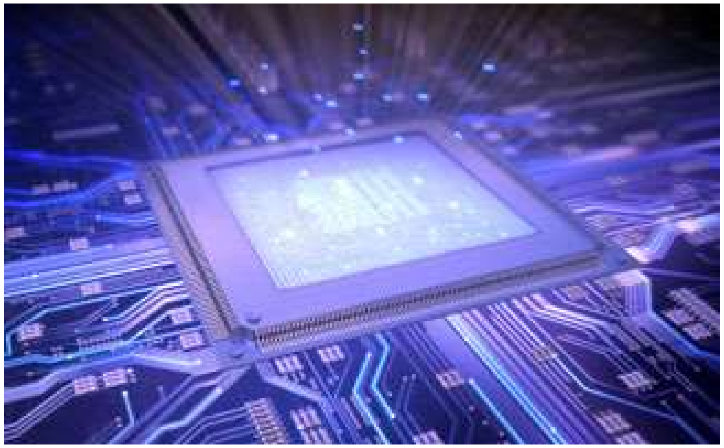
Parallel Computing

Parallel Software: Basics

Mohamed Zahran (aka Z)
mzahran@cs.nyu.edu
http://www.mzahran.com



The burden is on software

- From now on…
  - In shared memory systems:
    - Start a single process and fork threads.
    - Threads carry out tasks.
  - In distributed memory systems:
    - Start multiple processes.
    - Processes carry out tasks.
  - When using accelerators (e.g. GPUs)
    - Start a process with one or more threads.
    - The thread launches task to be done on the GPU
    - GPU will do the same task on different data.

SPMD – single program multiple data

- SPMD programs consist of a single executable (i.e. single program) forked into different processes/threads, that can behave as if it were multiple different programs through the use of conditional branches.

```
if (I'm thread/process i)
    do this;
else
    do that;
```

Writing Parallel Programs

1. Divide the work among the processes/threads
   (a) so each process/thread gets roughly the same amount of work
   (b) and communication is minimized.
2. Arrange for the processes/threads to synchronize if needed.
3. Arrange for communication among processes/threads.

Example of an easily parallelizable piece of software

```
double x[n], y[n];
...
for (i = 0; i < n; i++)
    x[i] += y[i];
```

Shared Memory Systems (Threads)

Shared Memory

- **Dynamic threads:** Master thread waits for work, forks new threads, and when threads are done, they terminate
  - \+ Efficient use of resources
  - \- thread creation and termination is time consuming
- **Static threads:** Pool of threads created and are allocated work, but do not terminate until cleanup.
  - \+ Better performance
  - \- potential waste of system resources

Nondeterminism

```
. . .
printf ( "Thread %d: my_val = %d\n" ,
         my_rank , my_x ) ;
. . .
```

Executed by several threads

possibility 1

Thread 1: my_val = 19

Thread 0: my_val = 7

possibility 2

Thread 0: my_val = 7

Thread 1: my_val = 19

Effect of Nondeterminism

- Race condition
- Critical section
  - Mutual exclusion
  - Need to enforce mutual exclusion through locks (mutex, semaphore, …)

```
my_val = Compute_val ( my_rank ) ;
Lock(&add_my_val_lock ) ;
x += my_val ;
Unlock(&add_my_val_lock ) ;
```

Important!!

What is the relationship between cache coherence and nondeterminism?
Isn't cache coherence enough to ensure determinism?

Busy-waiting

```
ok_for_1= false;
my_val = Compute_val ( my_rank ) ;
if ( my_rank == 1)
    while ( ! ok_for_1 ) ;  /* Busy−wait loop */
x += my_val ;  /* Critical section */
if ( my_rank == 0)
    ok_for_1 = true ;  /* Let thread 1 update x */
```

Notes:
Each thread has a unique ID (sometimes called rank)

For this example, assume:

- **ok_for_1** is shared among threads
- Each thread has its own: **my_rank** and **my_val**

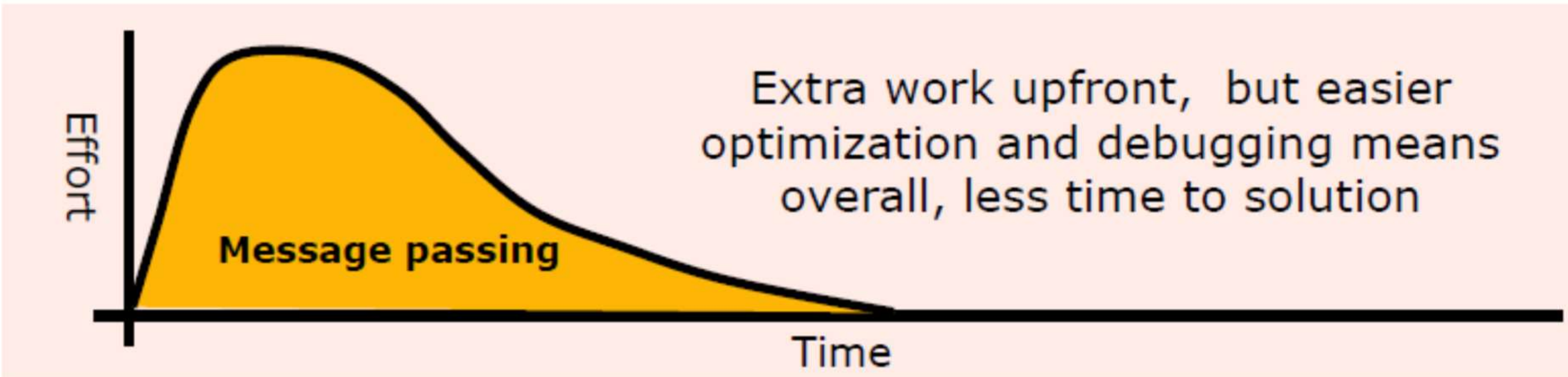
What is wrong with the above piece of code?

Distributed Memory Systems
(Processes)

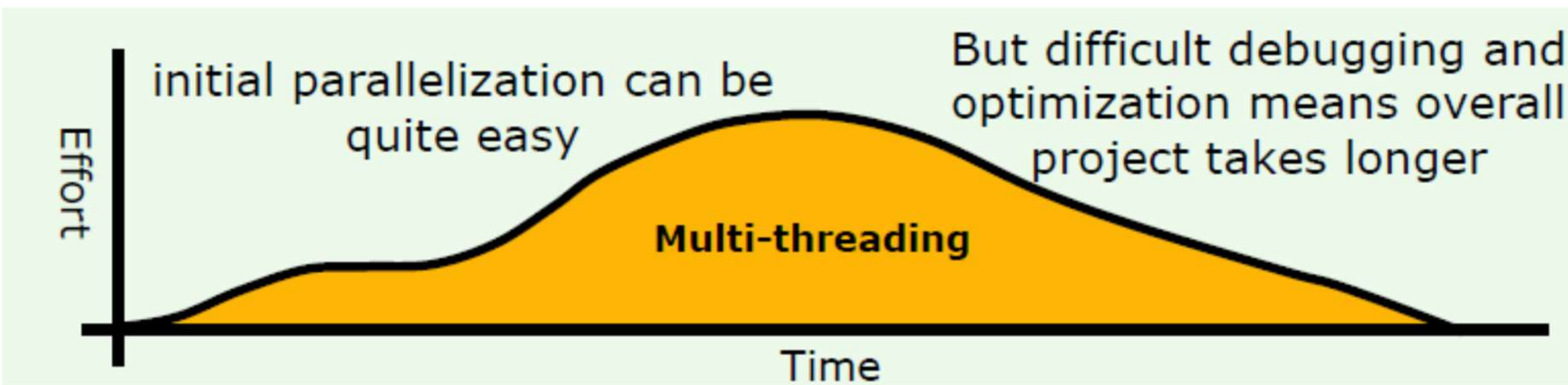
Distributed Memory: Message-Passing

```
char message [100] ;
. . .
my_rank = Get_rank();
i f ( my_rank == 1) {
    sprintf ( message , "Greetings from process 1" ) ;
    Send ( message , MSG_CHAR , 100 , 0 ) ; // send a msg of 100 char to process 0
} else if ( my_rank == 0) {
    Receive ( message , MSG_CHAR , 100 , 1 ) ;
    printf ( "Process 0 > Received: %s\n" , message ) ;
}
```

How do shared-memory and distributed-memory compare in terms of programmer's effort?



Distributed Memory



Shared Memory

Source: "Many Core Processors … Opportunities and Challenges" by Tim Mattson

We want to write a parallel program … Now what?

- We have a serial program.
  - How to parallelize it?
- We know that we need to divide work, ensure load balancing, manage synchronization, and reduce communication! → Nice! How to do that?
- Unfortunately: there is no mechanical process.
- **Ian Foster** has some nice framework.
  - Described in his book "Designing and Building Parallel Programs".

Foster's methodology (The PCAM Methodology)

1. Partitioning: divide the computation to be performed and the data operated on by the computation into small tasks.

   The focus here should be on identifying tasks that can be executed in parallel.

   This step brings out the parallelism in the algorithm

A checklist for problem partitioning

- Does your partition define at least an order of magnitude more tasks than there are processors/cores in your target computer? If not, you have little flexibility in subsequent design stages.

- Does your partition avoid redundant computation and storage requirements? If not, the resulting algorithm may not be scalable to deal with large problems.

- Are tasks of comparable size? If not, you may face load balancing issues later.

- Does the number of tasks scale with problem size? Ideally, an increase in problem size should increase the number of tasks rather than the size of individual tasks.

- Have you identified several alternative partitions?

Foster's methodology (The PCAM Methodology)

2. Communication: determine what communication needs to be carried out among the tasks identified in the previous step.

A checklist for communication

- Do all tasks perform about the same number of communication operations? Unbalanced communication requirements suggest a nonscalable construct. Revisit your design to see whether communication operations can be distributed more equitably. For example, if a frequently accessed data structure is encapsulated in a single task, consider distributing or replicating this data structure.
- Does each task communicate only with a small number of neighbors? If each task must communicate with many other tasks, evaluate the possibility of formulating this global communication in terms of a local communication structure.
- Are communication operations able to proceed concurrently? If not, your algorithm is likely to be inefficient and nonscalable.

Foster's methodology (The PCAM Methodology)

3. Agglomeration or aggregation: combine tasks and communications identified in the first step into larger tasks.

   For example, if task A must be executed before task B can be executed, it may make sense to aggregate them into a single composite task.

A checklist for agglomeration

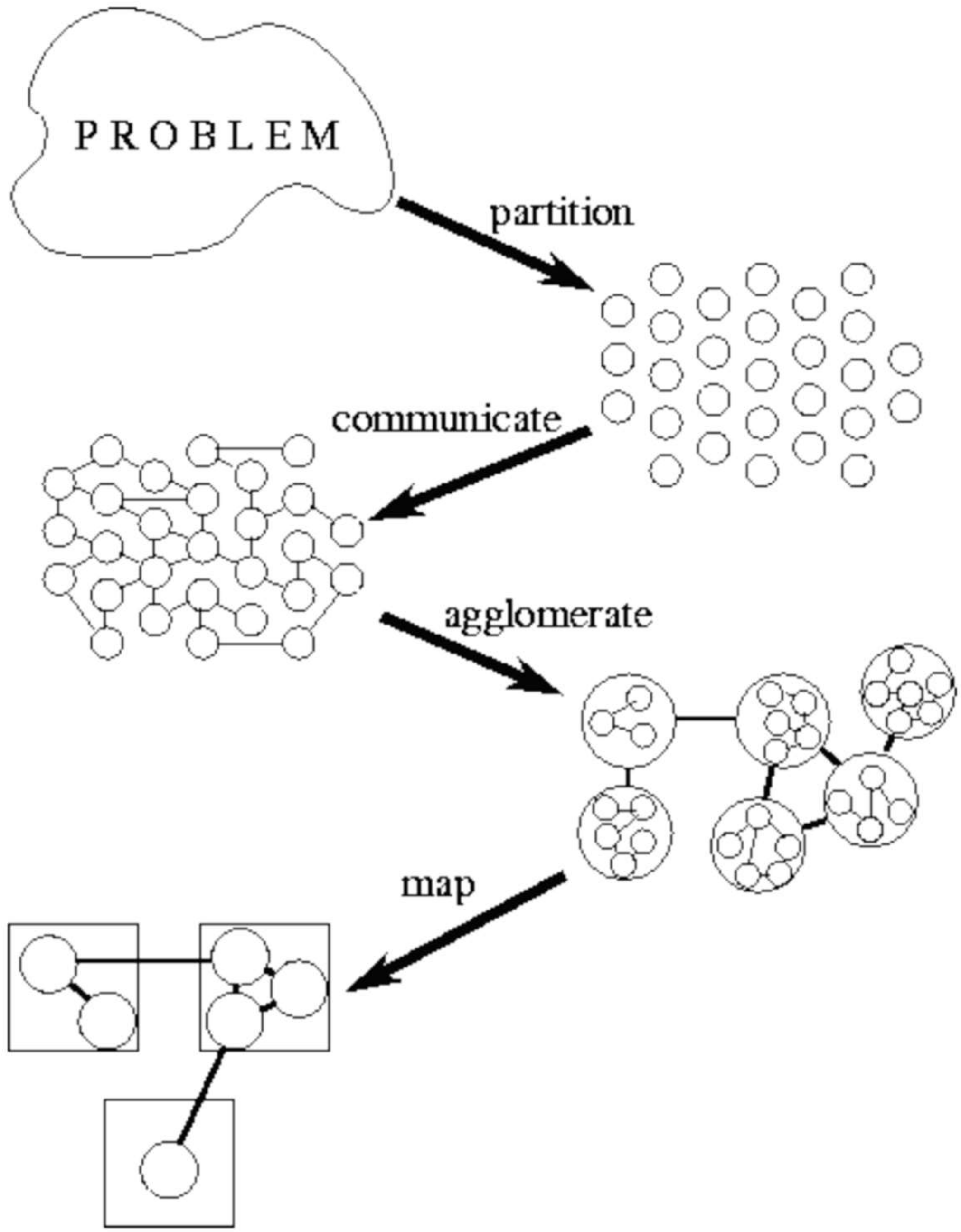
- Has agglomeration reduced communication costs by increasing locality? If not, examine your algorithm to determine whether this could be achieved using an alternative agglomeration strategy.
- Have you explored replicated data or computation to reduce communication cost and explored the benefits and costs?
- Has agglomeration affected load balancing in a negative way? You may need to check several agglomeration alternatives.
- Check the effect of agglomeration on scalability.

Foster's methodology (The PCAM Methodology)

4. Mapping: assign the composite tasks identified in the previous step to processes/threads.

This should be done such that: -

- Communication is minimized.
- Each process/thread gets roughly the same amount of work.



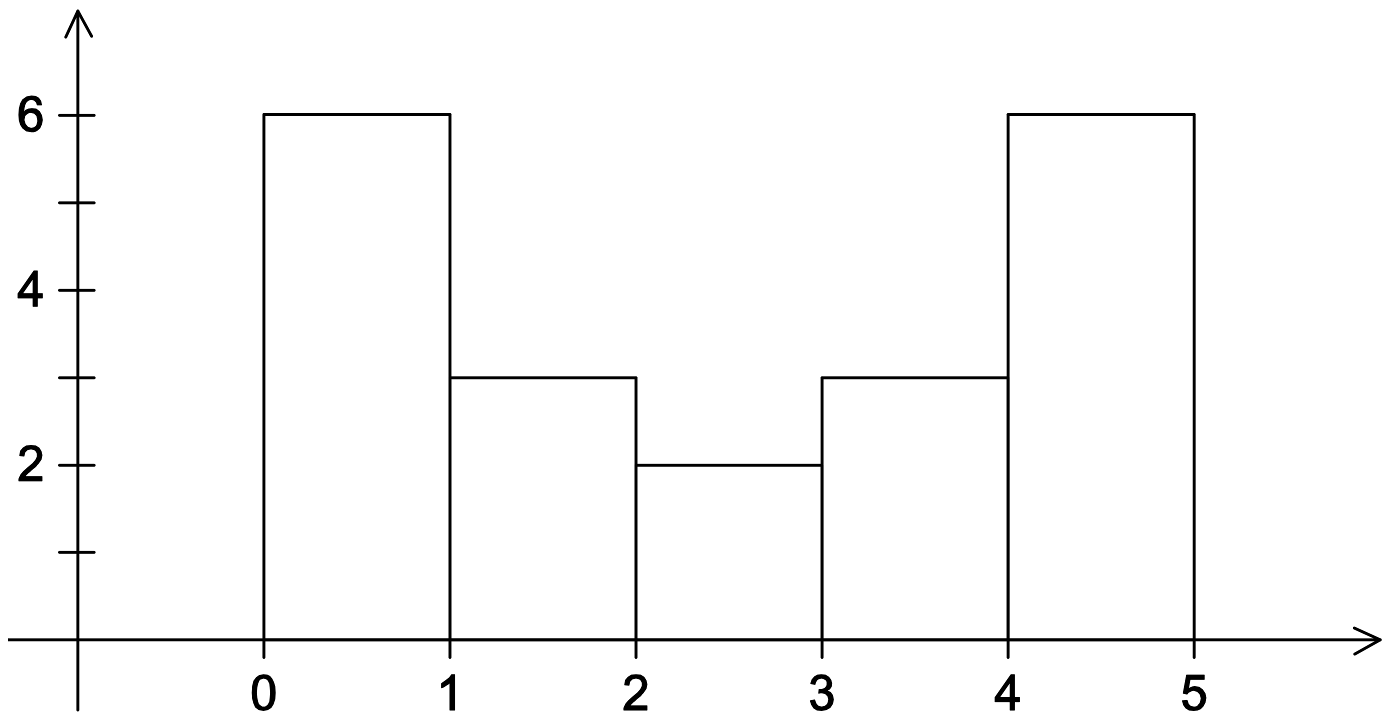
Source: “Designing and Building Parallel Programs” by Ian Foster

In General

- **[The P & C in PCAM model]** You design your program using machine-independent issues:
  - concurrency
  - scalability
  - ...
- **[The A & M in PCAM model]** You tweak your program to make the best use of the underlying hardware.

Example - histogram

- 1.3,2.9,0.4,0.3,1.3,4.4,1.7,0.4,3.2,0.3,4.9, 2.4,3.1,4.4,3.9,0.4,4.2,4.5,4.9,0.9



Serial program - input

1. The number of measurements: data_count
2. An array of data_count floats: data
3. The minimum value for the bin containing the smallest values: min_meas
4. The maximum value for the bin containing the largest values: max_meas
5. The number of bins: bin_count

- Data[0] = 1.3
- Data[1] = 2.9
- Data[2] = 0.4
- Data[3] = 0.3
- Data[4] = 1.3
- Data[5] = 4.4
- Data[6] = 1.7
- Data[7] = 0.4
- Data[8] = 3.2
- Data[9] = 0.3
- Data[10] = 4.9
- Data[11] = 2.4
- Data[12] = 3.1
- Data[13] = 4.4
- Data[14] = 3.9,
- Data[15] = 0.4
- Data[16] = 4.2
- Data[17] = 4.5
- Data[18] = 4.9
- Data[19] = 0.9

data_count = 20

- Data[0] = 1.3
- Data[1] = 2.9
- Data[2] = 0.4
- Data[3] = 0.3
- Data[4] = 1.3
- Data[5] = 4.4
- Data[6] = 1.7
- Data[7] = 0.4
- Data[8] = 3.2
- Data[9] = 0.3
- Data[10] = 4.9
- Data[11] = 2.4
- Data[12] = 3.1
- Data[13] = 4.4
- Data[14] = 3.9,
- Data[15] = 0.4
- Data[16] = 4.2
- Data[17] = 4.5
- Data[18] = 4.9
- Data[19] = 0.9

data_count = 20

min_meas = 0.3

max_meas = 4.9

bin_count = 5

Serial program - output

1. bin_maxes : an array of bin_count floats → store the upper bound of each bin

2. bin_counts : an array of bin_count ints → stores the number of elements in each bin

- Data[0] = 1.3
- Data[1] = 2.9
- Data[2] = 0.4
- Data[3] = 0.3
- Data[4] = 1.3
- Data[5] = 4.4
- Data[6] = 1.7
- Data[7] = 0.4
- Data[8] = 3.2
- Data[9] = 0.3
- Data[10] = 4.9
- Data[11] = 2.4
- Data[12] = 3.1
- Data[13] = 4.4
- Data[14] = 3.9,
- Data[15] = 0.4
- Data[16] = 4.2
- Data[17] = 4.5
- Data[18] = 4.9
- Data[19] = 0.9

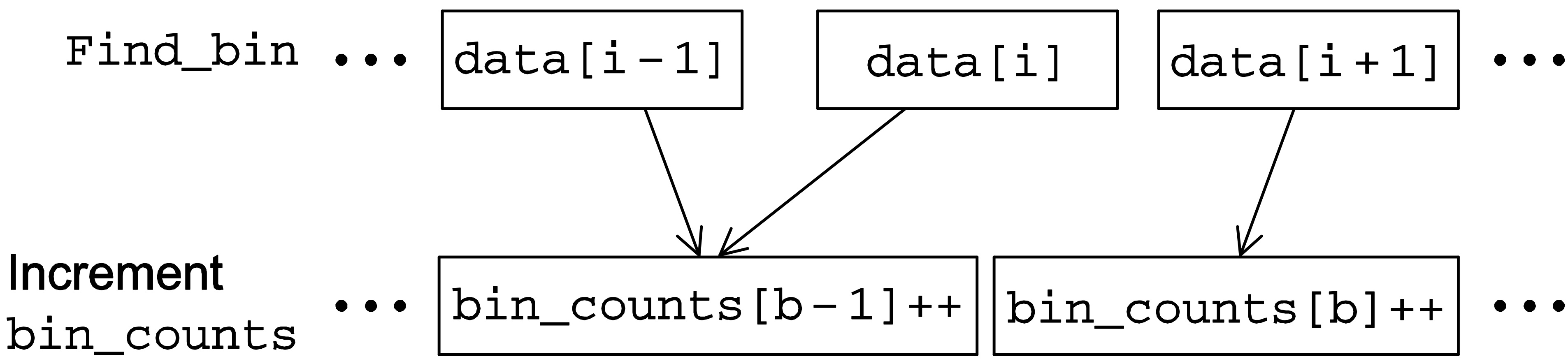
bin_maxes[0] = 0.9
bin_maxes[1] = 1.7
bin_maxes[2] = 2.9
bin_maxes[3] = 3.9
bin_maxes[4] = 4.9

bin_counts[0] = 6
bin_counts[1] = 3
bin_counts[2] = 2
bin_counts[3] = 3
bin_counts[4] = 6

Serial Program

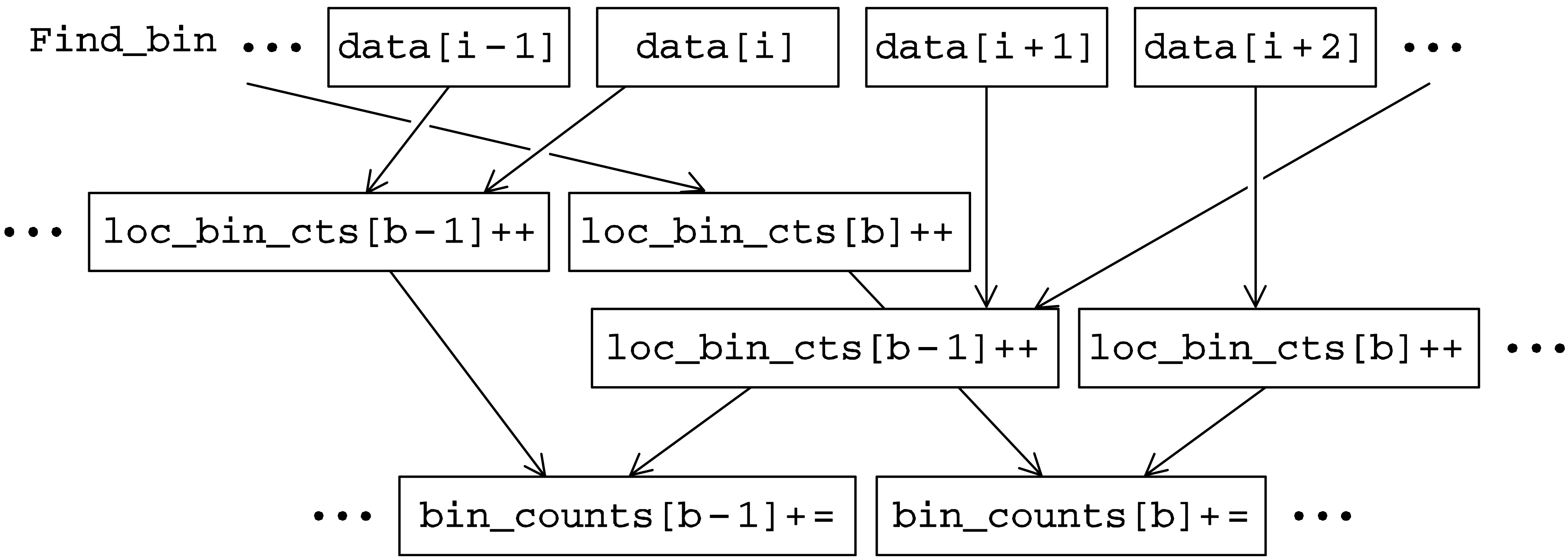
```
int bin = 0;
for( i = 0; i < data_count; i++){
  bin = find_bin(data[i], ...);
  bin_counts[bin]++;
}
```

First two stages of Foster's Methodology

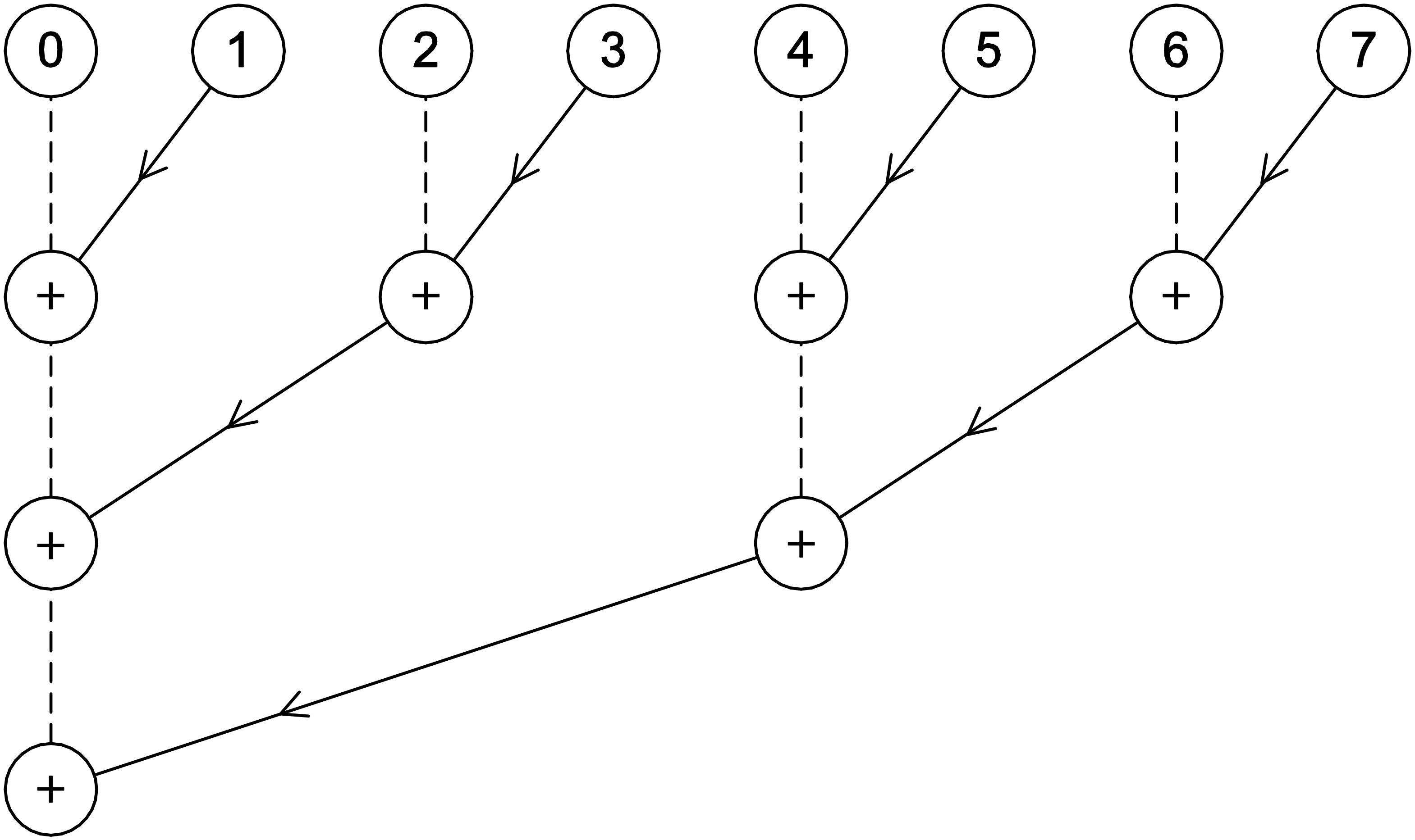


Find_bin returns the bin that data[i] belongs to.

Alternative definition of tasks and communication



Adding the local arrays



Conclusions

- Parallel Program Design
  - Partition
  - Determine communication
  - Aggregate (if needed)
  - Map