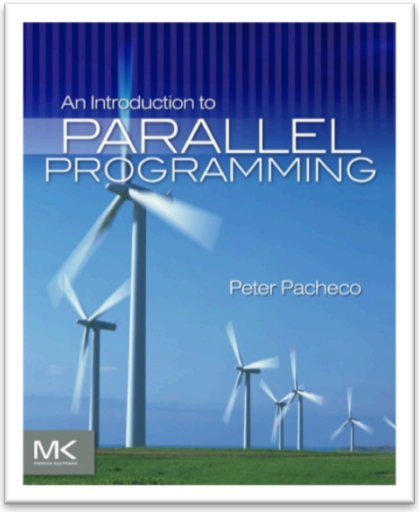
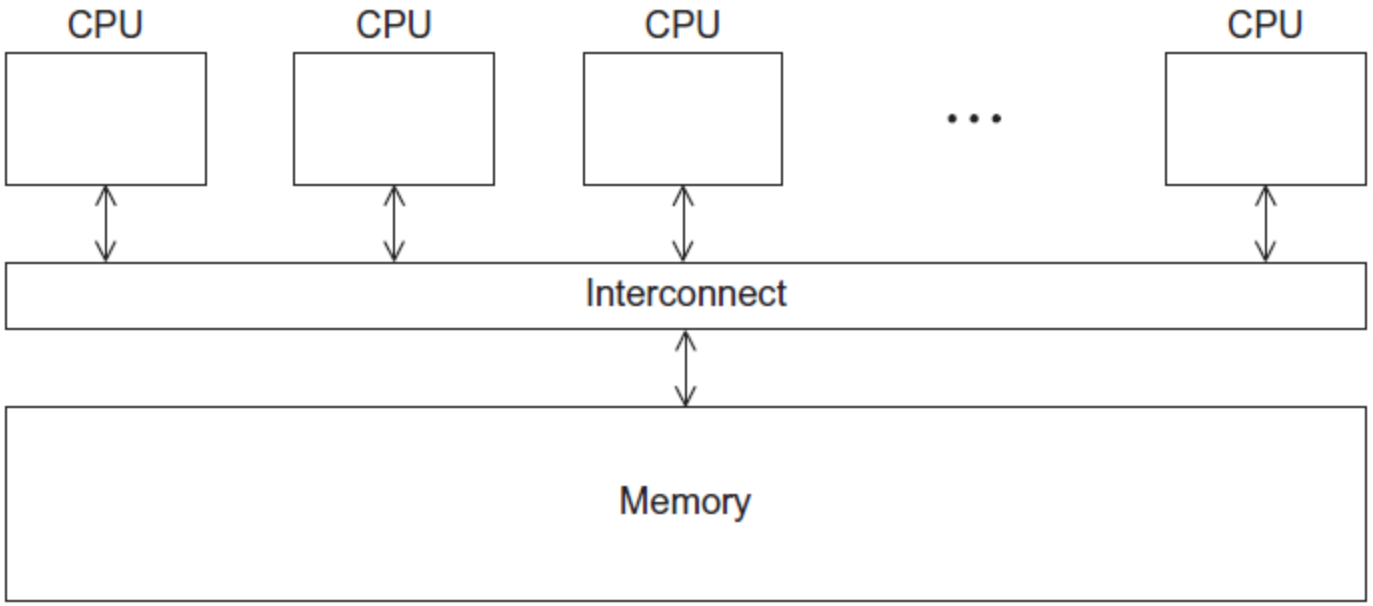


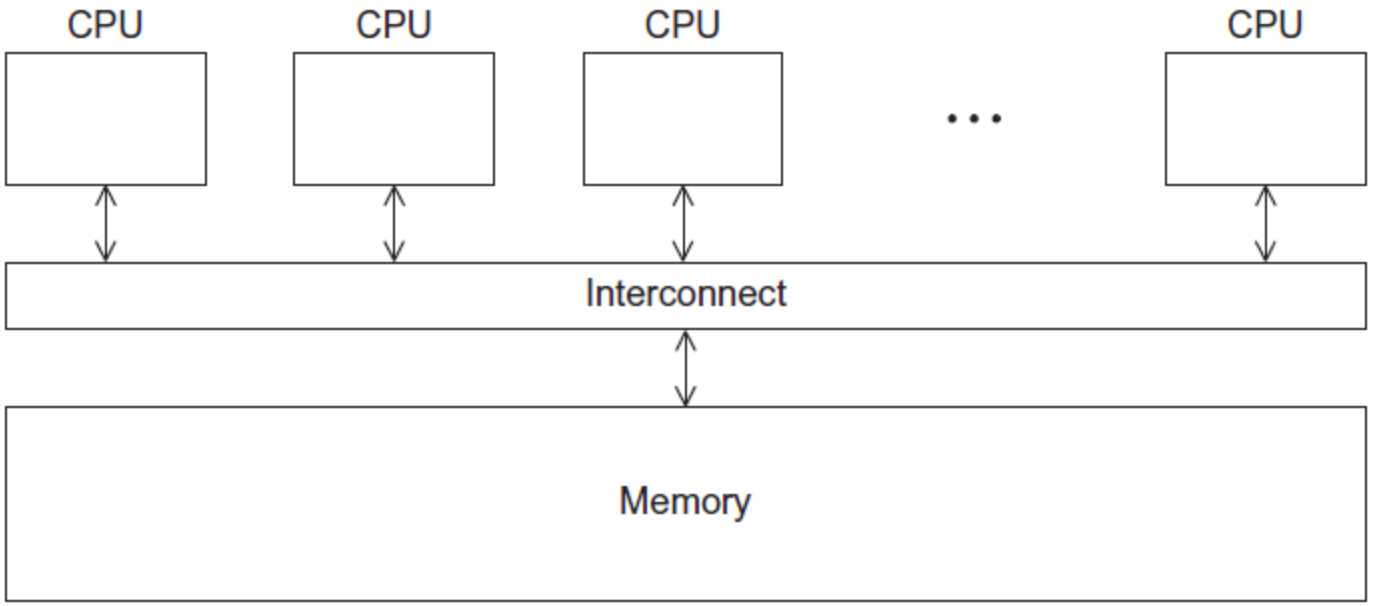

# Chapter 4

## Shared Memory Programming with Pthreads

# A Shared Memory System



# A Shared Memory System



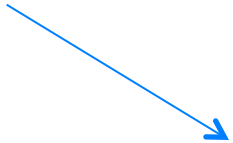

**Last class: *ping-pong* and *false sharing* problems**

# POSIX®Threads

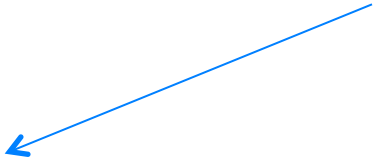
- Also known as Pthreads.
- A standard for Unix-like operating systems.
- A library that can be linked with C programs.
- Specifies an application programming interface (API) for multi-threaded programming.

# Starting the Threads

pthread.h



pthread_t



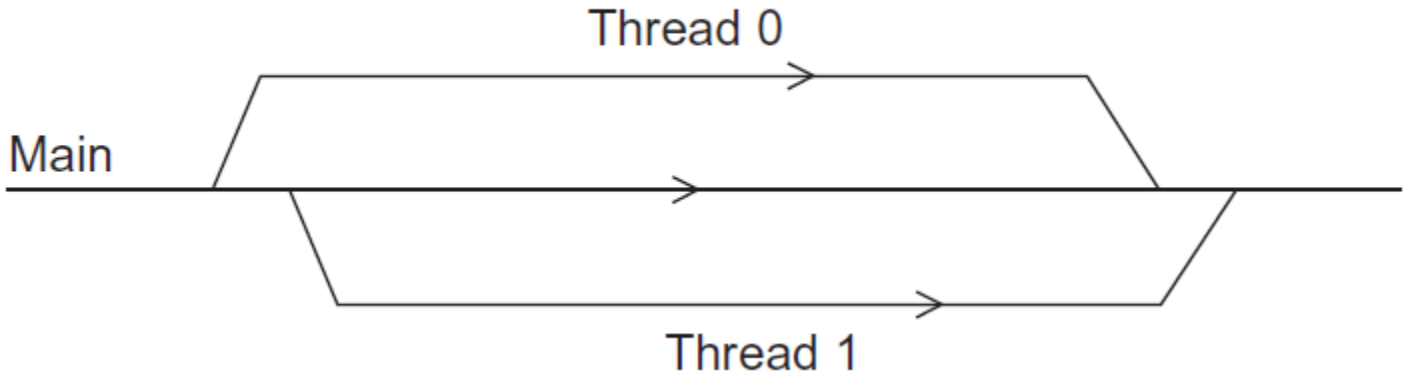
**One object for each thread.**

```
int pthread_create (
        pthread_t*  thread_p /* out */ ,
        const pthread_attr_t*  attr_p /* in */ ,
        void*  (*start_routine ) ( void ) /* in */ ,
        void*  arg_p /* in */ ) ;
```

# Function started by pthread_create

- Prototype:
  void* thread_function ( void* args_p ) ;
- Void* can be cast to any pointer type in C.
- So args_p can point to a list containing one or more values needed by thread_function.
- Similarly, the return value of thread_function can point to a list of one or more values.

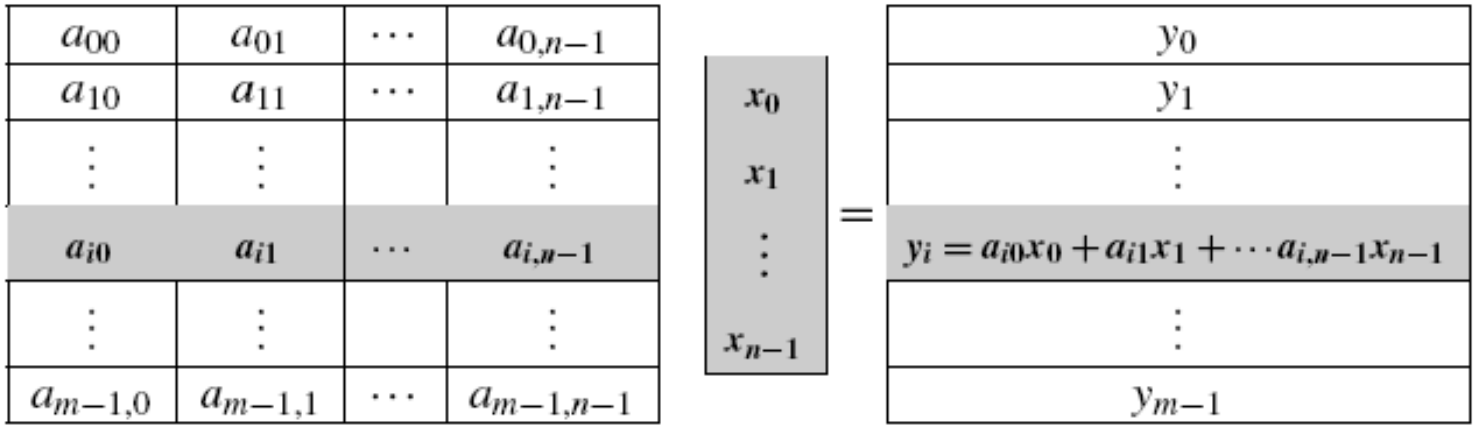
# Running the Threads




Main thread forks and joins two threads.

# Stopping the Threads

- We call the function pthread_join once for each thread.
- A single call to pthread_join will wait for the thread associated with the pthread_t object to complete.




# MATRIX-VECTOR MULTIPLICATION IN PTHREADS

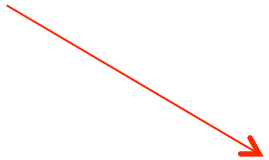
# Serial pseudo-code

```
/* For each row of A */
for (i = 0; i < m; i++) {
    y[i] = 0.0;
    /* For each element of the row and each element of x */
    for (j = 0; j < n; j++)
        y[i] += A[i][j]* x[j];
}
```

$$y_i = \sum_{j=0}^{n-1} a_{ij} x_j$$

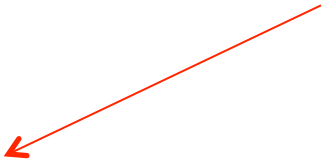
# Using 3 Pthreads

| Thread | Components of y |
|---|---|
| 0 | y[0], y[1] |
| 1 | y[2], y[3] |
| 2 | y[4], y[5] |



thread 0

```
y[0] = 0.0;
for (j = 0; j < n; j++)
   y[0] += A[0][j]* x[j];
```



general case

```
y[i] = 0.0;
for (j = 0; j < n; j++)
   y[i] += A[i][j]*x[j];
```

# Pthreads matrix-vector multiplication

```
void *Pth_mat_vect(void* rank) {
   long my_rank = (long) rank;
   int i, j;
   int local_m = m/thread_count;
   int my_first_row = my_rank*local_m;
   int my_last_row = (my_rank+1)*local_m - 1;

   for (i = my_first_row; i <= my_last_row; i++) {
      y[i] = 0.0;
      for (j = 0; j < n; j++)
         y[i] += A[i][j]*x[j];
   }

   return NULL;
}  /* Pth_mat_vect */
```

# PARALLEL PROGRAM DESIGN

# Foster's 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.

# Foster's methodology

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

# Foster's 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.

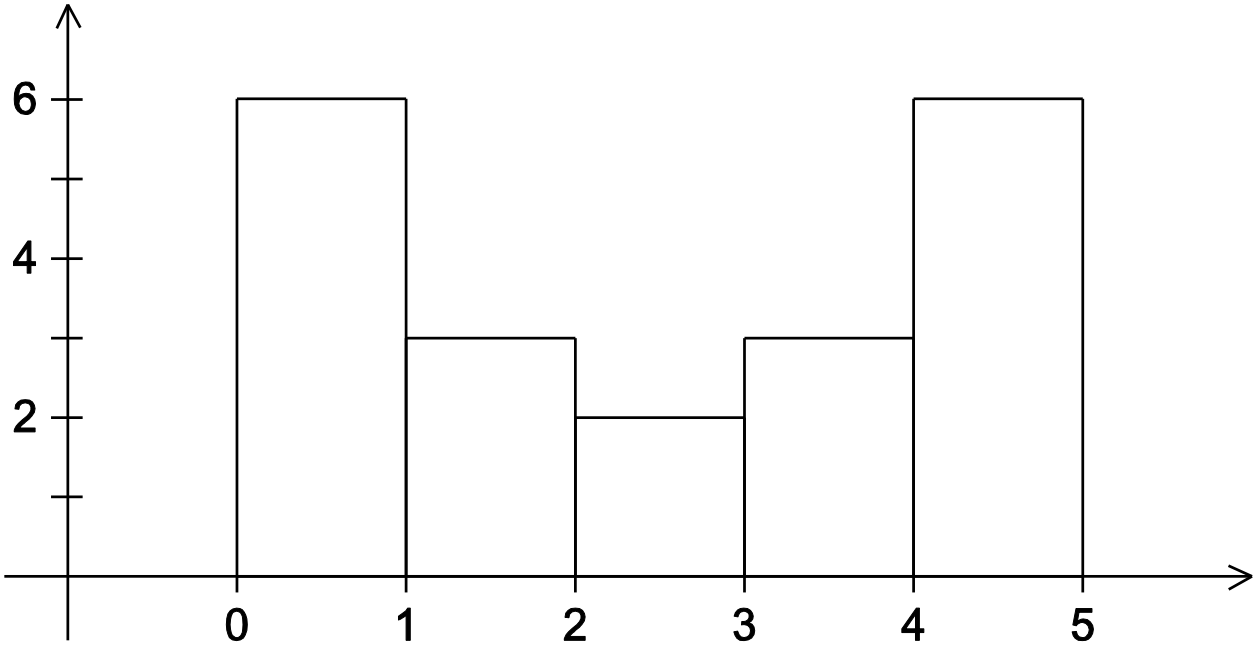
# Foster's methodology

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

   This should be done so that communication is minimized, and each process/thread gets roughly the same amount of work.

# 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

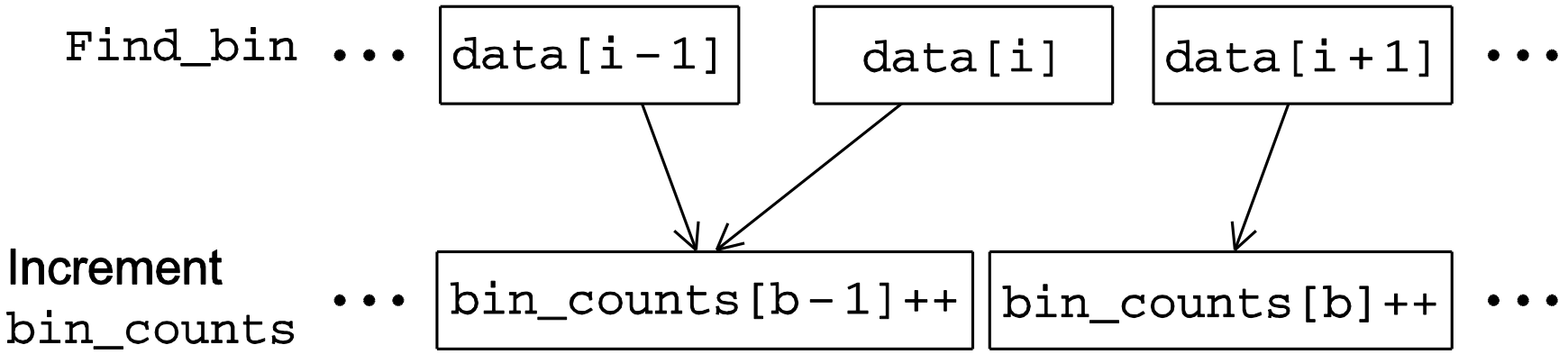
1. The number of measurements: data_count
2. An array of data_count floats: data
3. The minimum value for the bin containing the smallest values: min_meas
4. The maximum value for the bin containing the largest values: max_meas
5. The number of bins: bin_count

# Serial program - output

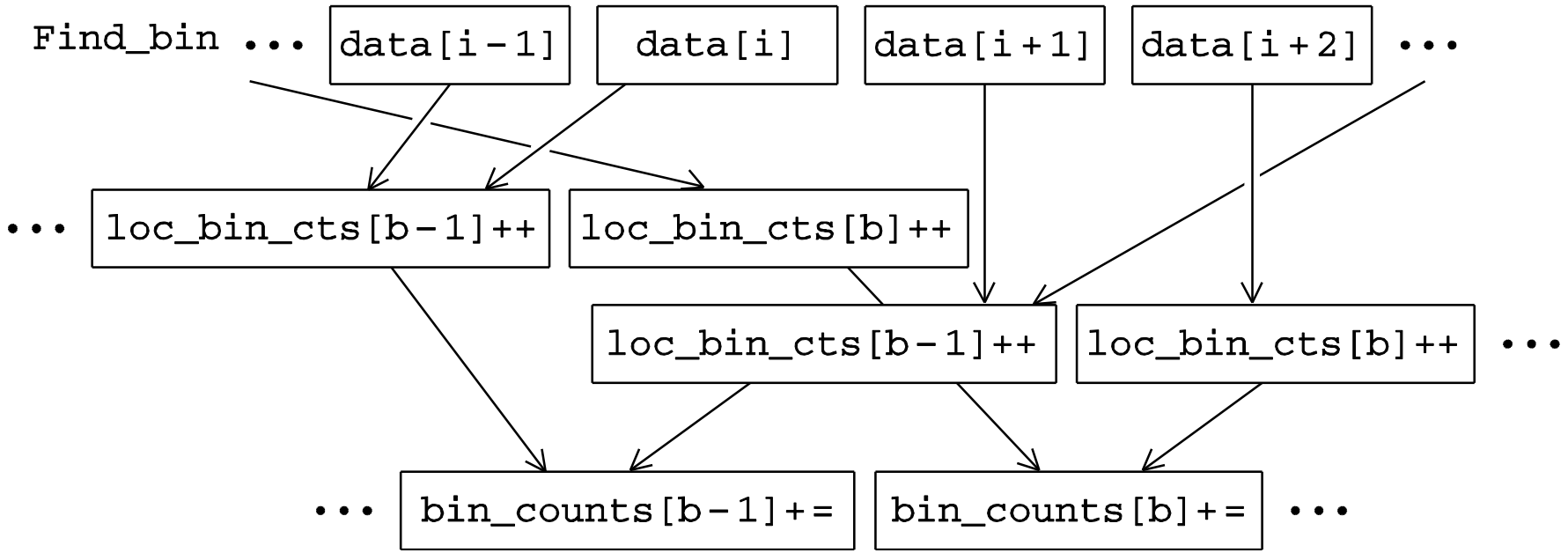
1. bin_maxes : an array of bin_count floats

2. bin_counts : an array of bin_count ints

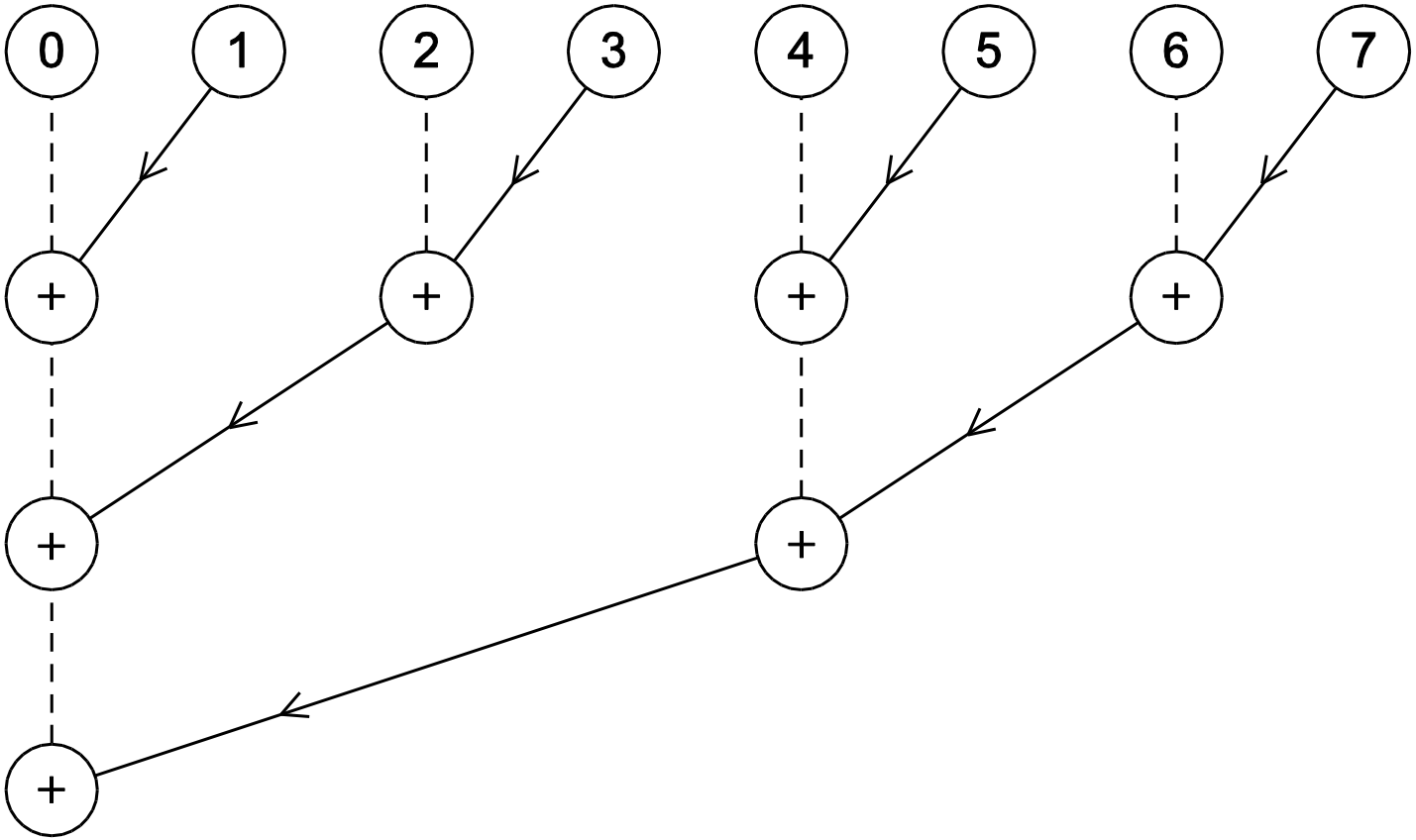
# First two stages of Foster's Methodology



# Alternative definition of tasks and communication



# Adding the local arrays



# CRITICAL SECTIONS

# Estimating π

$$\pi = 4\left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \cdots + (-1)^n \frac{1}{2n+1} + \cdots\right)$$

```
double factor = 1.0;
double sum = 0.0;
for (i = 0; i < n; i++, factor = -factor) {
    sum += factor/(2*i+1);
}
pi = 4.0*sum;
```

# Using a dual core processor

| | $n$ | | | |
|---|---|---|---|---|
| | $10^5$ | $10^6$ | $10^7$ | $10^8$ |
| $\pi$ | 3.14159 | 3.141593 | 3.1415927 | 3.14159265 |
| 1 Thread | 3.14158 | 3.141592 | 3.1415926 | 3.14159264 |
| 2 Threads | 3.14158 | 3.141480 | 3.1413692 | 3.14164686 |

Note that as we increase n, the estimate with one thread gets better and better.

# A thread function for computing π

```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;

   if (my_first_i % 2 == 0)  /* my_first_i is even */
      factor = 1.0;
   else  /* my_first_i is odd */
      factor = -1.0;

   for (i = my_first_i; i < my_last_i; i++, factor = -factor) {
      sum += factor/(2*i+1);
   }

   return NULL;
}  /* Thread_sum */
```

# Possible race condition

| Time | Thread 0 | Thread 1 |
|---|---|---|
| 1 | Started by main thread | |
| 2 | Call `Compute()` | Started by main thread |
| 3 | Assign `y = 1` | Call `Compute()` |
| 4 | Put `x=0` and `y=1` into registers | Assign `y = 2` |
| 5 | Add 0 and 1 | Put `x=0` and `y=2` into registers |
| 6 | Store 1 in memory location `x` | Add 0 and 2 |
| 7 | | Store 2 in memory location `x` |

# Busy-Waiting

- A thread repeatedly tests a condition, but, effectively, does no useful work until the condition has the appropriate value.

- Beware of optimizing compilers, though!

```
y = Compute(my_rank);
while (flag != my_rank);
x = x + y;
flag++;
```

flag initialized to 0 by main thread

# Pthreads global sum with busy-waiting

```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;

   if (my_first_i % 2 == 0)
      factor = 1.0;
   else
      factor = -1.0;

   for (i = my_first_i; i < my_last_i; i++, factor = -factor) {
      while (flag != my_rank);
      sum += factor/(2*i+1);
      flag = (flag+1) % thread_count;
   }

   return NULL;
}  /* Thread_sum */
```

# Global sum function with critical section after loop (1)

```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor, my_sum = 0.0;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;

   if (my_first_i % 2 == 0)
      factor = 1.0;
   else
      factor = -1.0;
```

# Global sum function with critical section after loop (2)

```
    for (i = my_first_i; i < my_last_i; i++, factor = -factor)
       my_sum += factor/(2*i+1);

    while (flag != my_rank);
    sum += my_sum;
    flag = (flag+1) % thread_count;

    return NULL;
}   /* Thread_sum */
```

# Mutexes

- A thread that is busy-waiting may continually use the CPU accomplishing nothing.
- Mutex (mutual exclusion) is a special type of variable that can be used to restrict access to a critical section to a single thread at a time.

# Mutexes


- Used to guarantee that one thread "excludes" all other threads while it executes the critical section.

- The Pthreads standard includes a special type for mutexes: pthread_mutex_t.

```
int pthread_mutex_init(
      pthread_mutex_t*              mutex_p   /* out */
      const pthread_mutexattr_t*    attr_p    /* in  */);
```

# Mutexes

- When a Pthreads program finishes using a mutex, it should call

```
int pthread_mutex_destroy(pthread_mutex_t* mutex_p  /* in/out */);
```

- In order to gain access to a critical section a thread calls

```
int pthread_mutex_lock(pthread_mutex_t* mutex_p  /* in/out */);
```

# Mutexes

- When a thread is finished executing the code in a critical section, it should call

```
int pthread_mutex_unlock(pthread_mutex_t* mutex_p  /* in/out */);
```

# Global sum function that uses a mutex (1)

```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;
   double my_sum = 0.0;

   if (my_first_i % 2 == 0)
      factor = 1.0;
   else
      factor = -1.0;
```

# Global sum function that uses a mutex (2)

```
   for (i = my_first_i; i < my_last_i; i++, factor = -factor) {
      my_sum += factor/(2*i+1);
   }
   pthread_mutex_lock(&mutex);
   sum += my_sum;
   pthread_mutex_unlock(&mutex);

   return NULL;
}  /* Thread_sum */
```

| Threads | Busy-Wait | Mutex |
|---|---|---|
| 1 | 2.90 | 2.90 |
| 2 | 1.45 | 1.45 |
| 4 | 0.73 | 0.73 |
| 8 | 0.38 | 0.38 |
| 16 | 0.50 | 0.38 |
| 32 | 0.80 | 0.40 |
| 64 | 3.56 | 0.38 |

$$\frac{T_{\text{serial}}}{T_{\text{parallel}}} \approx \texttt{thread\_count}$$

Run-times (in seconds) of π programs using n = 108 terms on a system with two four-core processors.

| Time | flag | Thread | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 1 | 2 | 3 | 4 |
| 0 | 0 | crit sect | busy wait | susp | susp | susp |
| 1 | 1 | terminate | crit sect | susp | busy wait | susp |
| 2 | 2 | — | terminate | susp | busy wait | busy wait |
| ⋮ | ⋮ | | | ⋮ | ⋮ | ⋮ |
| ? | 2 | — | — | crit sect | susp | busy wait |

Possible sequence of events with busy-waiting and more threads than cores.