COMP/CS 605: Introduction to Parallel Computing
Lecture : Shared Memory Programming using PThreads

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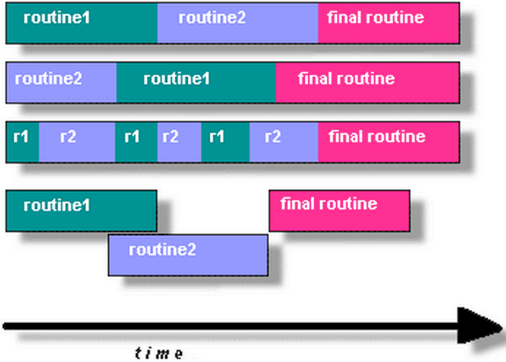
Introduction to Shared Memory Programming using PThreads.

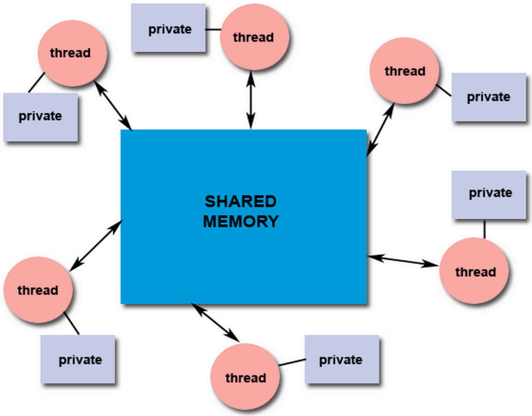
Shared Memory System

Best candidates:

- can be organized into discrete, independent tasks which can execute concurrently
- routines can be interchanged, interleaved and/or overlapped in real time



Shared Memory System



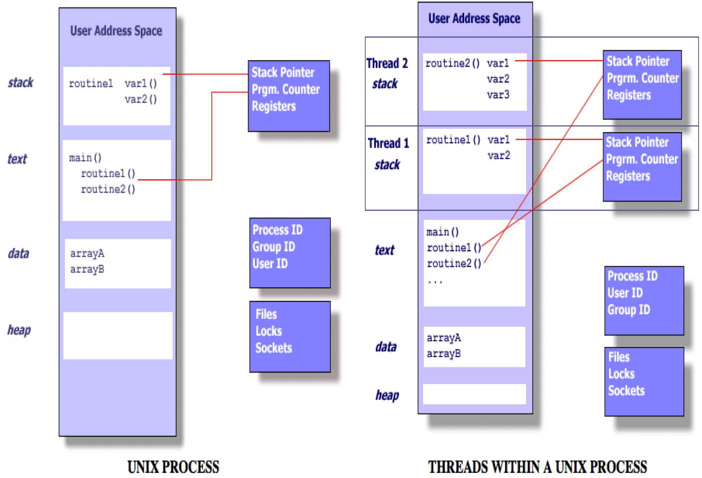
What is a Process?

- A process is an instance of a running (or suspended) program.
- Can be "muti-threaded," created by OS, requires a fair amount of "overhead"
- Process ID, process group ID, user ID, and group ID, Environment
- program instructions, registers, stack, heap, signals, libraries
- working directory, file descriptors
- Inter-process communication tools (such as message queues, pipes, semaphores, or shared memory).

Ref: `http://www.bottomupcs.com/elements_of_a_process.html`

What is a Thread?

- Threads are analogous to a light-weight process.
- Shared memory program: single process may have multiple threads of control.
- Independent stream of instructions, run inside processes
- Programs/procedures: runs independently from main program (e.g. multiple functions running concurrently)
- Example: main program (a.out) that contains a number of procedures that can be scheduled to run simultaneously and/or independently
- Thread models:
  - Manager/worker: a single thread, manager assigns work to other threads (workers).
  - Pipeline: task is broken into series of subops; each handled in series, but concurrently by another thread.
  - Peer: After the main thread (manager) creates other threads, it participates in the work.


User Address Space
stack
routine1 var1()
var2()
text
main()
routine1()
routine2()
data
arrayA
arrayB
heap
Stack Pointer
Prgm. Counter
Registers
Process ID
Group ID
User ID
Files
Locks
Sockets
UNIX PROCESS
User Address Space
Thread 2
stack
routine2() var1
var2
var3
Thread 1
stack
routine1() var1
var2
text
main()
routine1()
routine2()
...
data
arrayA
arrayB
heap
Stack Pointer
Prgm. Counter
Registers
Stack Pointer
Prgm. Counter
Registers
Process ID
User ID
Group ID
Files
Locks
Sockets
THREADS WITHIN A UNIX PROCESS

POSIX Threads

- Portable Operating System Interface
- IEEE's POSIX Threads Model (Pthreads):
    - programming models for threads in a UNIX platform
    - Pthreads are included in the international standards ISO/IEC9945-1
- 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.

The Pthreads API is only available on POSIXR systems such as: Linux, MacOS X, Solaris, HPUX,

Phreads: Hello World

```
 [frame=single,rulecolor=\color{blue}]
/* File:  pth_hello.c
 * Purpose:
 *    Illustrate basic use of pthreads:  create some threads,
 *    each of which prints a message.
 * Input:   none
 * Output:  message from each thread
 * Compile:  gcc -g -Wall -o pth_hello pth_hello.c -lpthread
 * Usage:    ./pth_hello <thread_count>
 * IPP:   Section 4.2 (p. 153 and ff.)
 */
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

const int MAX_THDS = 64;

/* Global variable:  accessible to all threads */
int thread_count;

void Usage(char* prog_name);
void *Hello(void* rank);  /* Thread function */

/*--------------------------------------------------*/
int main(int argc, char* argv[]) {
   /* Use long in case of a 64-bit system */
   long       thread;
   pthread_t* thread_handles;

   /* Get number of threads from command line */
   if (argc != 2) Usage(argv[0]);
   thread_count = strtol(argv[1], NULL, 10);
   if (thread_count<= 0 || thread_count>MAX_THDS)
          Usage(argv[0]);
```

```
thread_handles = malloc (thread_count*sizeof(pthread_t));

   for (thread = 0; thread < thread_count; thread++)
      pthread_create(&thread_handles[thread], NULL,
          Hello, (void*) thread);

   printf("Hello from the main thread\n");

   for (thread = 0; thread < thread_count; thread++)
      pthread_join(thread_handles[thread], NULL);

   free(thread_handles);
   return 0;
}  /* main */

/*--------------------------------------------------*/
void *Hello(void* rank) {
   /* Use long in case of a 64-bit system */
   long my_rank = (long) rank;

   printf("Hello from thread %ld of %d\n",
          my_rank, thread_count);

   return NULL;
}  /* Hello */

/*--------------------------------------------------*/
void Usage(char* prog_name) {
   fprintf(stderr, "usage: %s <number of threads>\n", prog_name);
   fprintf(stderr, "0 < number of threads <= %d\n", MAX_THREADS);
   exit(0);
}  /* Usage */
```

Compiling and running a Pthreads program

- Pthreads is a standard C library
- Compile like standard C code:

```
[gidget]  % gcc -g -Wall -o pth_hello pth_hello.c -lpthread
```

```
[gidget] % ./pth_hello 1
Hello from the main thread
Hello from thread 0 of 1

[gidget:dev/ipp.ch4/hello] mthomas% ./pth_hello 4
Hello from thread 0 of 4
Hello from thread 2 of 4
Hello from thread 1 of 4
Hello from the main thread
Hello from thread 3 of 4
```

Running a Pthreads program on tuckoo

[mthomas@tuckoo ch4] gcc -g -Wall -o pth_hello pth_hello.c -lpthread

```
[mthomas@tuckoo ch4] ./pth_hello 8

Hello from thread 0 of 8
Hello from thread 1 of 8
Hello from thread 2 of 8
Hello from thread 3 of 8
Hello from thread 4 of 8
Hello from thread 5 of 8
Hello from thread 6 of 8
Hello from the main thread
Hello from thread 7 of 8
```

Warning about global variables

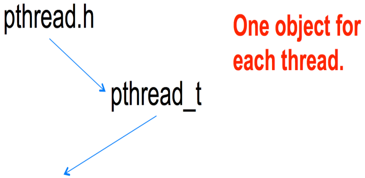
- All threads have access to the same global, shared memory
- Threads also have their own private data
- Limit use of global variables to situations where they are really needed:
  - Shared variables.
- Programmers are responsible for synchronizing access (protecting) globally shared data.
  - Can introduce subtle and confusing bugs

POSIX Threads API: Four Main Groups

- Thread management: Routines that work directly on threads - creating, detaching, joining, etc.
- Mutexes: Routines that deal with synchronization, called a "mutex", which is an abbreviation for "mutual exclusion".
- Condition variables: Routines that address communications between threads that share a mutex. Includes functions to create, destroy, wait and signal based upon specified variable values.
- Synchronization: Routines that manage read/write locks and barriers.

Starting Threads: *pthread_create*()

- Processes in MPI are usually started by a script.
- In Pthreads the threads are started by the program executable.




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

pthread_t objects

- Opaque
- The actual data that they store is system-specific.
- Their data members aren't directly accessible to user code.
- However, the Pthreads standard guarantees that a pthread_t object does store enough information to uniquely identify the thread with which it's associated.

A closer look (1)

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

We won't be using, so we just pass NULL.

Allocate before calling.

A closer look (2)

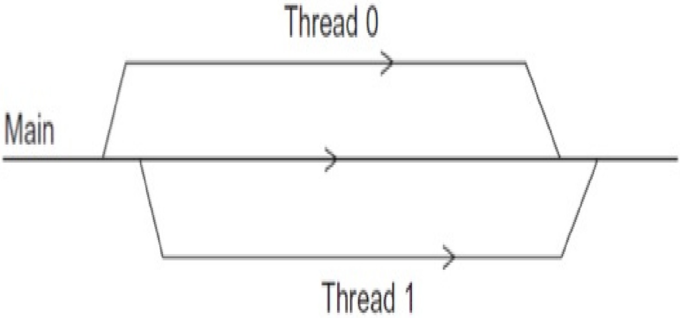
```
int pthread_create (
        pthread_t*  thread_p /* out */ ,
        const pthread_attr_t*  attr_p /* in */ ,
        void*  (*start_routine ) ( void ) /* in */ ,
        void*  arg_p /* in */ ) ;
```

Pointer to the argument that should be passed to the function *start_routine*.

The function that the thread is to run.

Function started by pthread_create

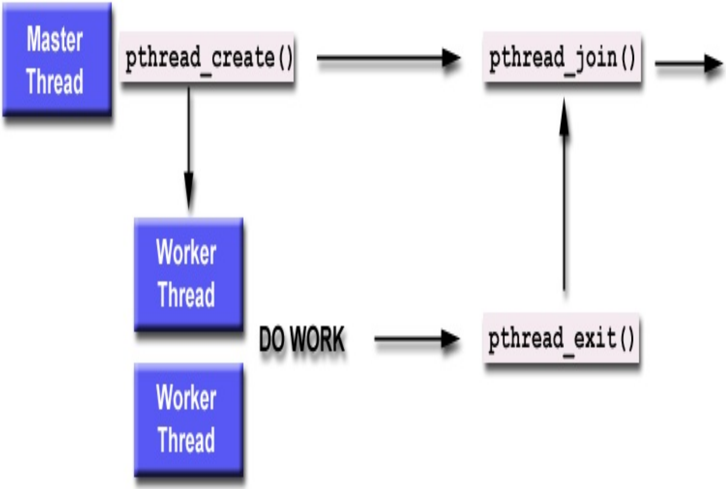
- Prototype:
  void* thread_function (void* args_p) ;
- Void* can be cast to any pointer type in C.
- So args_p can point to a list containing one or more values needed by thread_function.
- Similarly, the return value of thread_function can point to a list of one or more values.



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.



Source: `https://computing.llnl.gov/tutorials/pthreads/`

Matrix-Vector Multiplication with Pthreads

Definition: Let A be an $[m\,x\,n]$ matrix, and x be a be an $[n\,x\,1]$, then y will be a vector with the dimensions $[m\,x\,1]$.

Then $$y_j = \sum_{t=1}^{m} a_{it}x_t = a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{m-1,1}b_{m-1}$$

$$\begin{bmatrix} a_{00} \ \dots \ a_{0j} \ \dots \ a_{0,n-1} \\ \dots \\ \mathbf{a_{i0}} \ \dots \ a_{ij} \ \dots \ a_{i,n-1} \\ \dots \\ a_{m-1,0} \ \dots \ a_{m-1,j} \ \dots \ a_{m-1,n-1} \end{bmatrix} \bullet \begin{bmatrix} \mathbf{x_0} \\ \dots \\ \mathbf{x_i} \\ \dots \\ \mathbf{x_n} \end{bmatrix} = \begin{bmatrix} y_0 \\ \dots \\ \mathbf{y_j} \\ \dots \\ y_{m-1} \end{bmatrix}$$

a_{00}	a_{01}	$\cdots$	$a_{0,n-1}$
a_{10}	a_{11}	$\cdots$	$a_{1,n-1}$
$\vdots$	$\vdots$		$\vdots$
a_{i0}	a_{i1}	$\cdots$	$a_{i,n-1}$
$\vdots$	$\vdots$		$\vdots$
$a_{m-1,0}$	$a_{m-1,1}$	$\cdots$	$a_{m-1,n-1}$

x_0
x_1
$\vdots$
x_{n-1}

=

y_0
y_1
$\vdots$
$y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots a_{i,n-1}x_{n-1}$
$\vdots$
y_{m-1}

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, 6 elements

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

```
/* File:
 *     pth_mat_vect.c
 *
 * *
 * Compile:  gcc -g -Wall -o pth_mat_vect pth_mat_vect.c -lpthread
 * Usage:
 *     pth_mat_vect <thread_count>
 *
 * IPP:    Section 4.3 (pp. 159 and ff.).  Also Section 4.10 (pp. 191)
 */
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

/* Global variables */
int     thread_count;
int     m, n;
double* A;
double* x;
double* y;

/* Serial functions */
void Usage(char* prog_name);
void Read_matrix(char* prompt, double A[], int m, int n);
void Read_vector(char* prompt, double x[], int n);
void Print_matrix(char* title, double A[], int m, int n);
void Print_vector(char* title, double y[], double m);

/* Parallel function */
void *Pth_mat_vect(void* rank);
```

Pthreads matrix-vector multiplication

```
int main(int argc, char* argv[]) {
   long       thread;
   pthread_t* thread_handles;

   if (argc != 2) Usage(argv[0]);
   thread_count = atoi(argv[1]);
   thread_handles = malloc(thread_count*sizeof(pthread_t));

   printf("Enter m and n\n");    scanf("%d%d", &m, &n);

   A = malloc(m*n*sizeof(double));
   x = malloc(n*sizeof(double));
   y = malloc(m*sizeof(double));

   Read_matrix("Enter the matrix", A, m, n);   Print_matrix("We read", A, m, n);
   Read_vector("Enter the vector", x, n);     Print_vector("We read", x, n);

   for (thread = 0; thread < thread_count; thread++)
      pthread_create(&thread_handles[thread], NULL,   Pth_mat_vect, (void*) thread);

   for (thread = 0; thread < thread_count; thread++)
      pthread_join(thread_handles[thread], NULL);

   Print_vector("The product is", y, m);

   free(A);   free(x);    free(y);
   return 0;
```

Pthreads matrix-vector multiplication

```
/*------------------------------------------------------------------
 * Function:  Usage
 * Purpose:   print a message showing what the command line should
 *            be, and terminate
 * In arg :   prog_name
 */
void Usage (char* prog_name) {
   fprintf(stderr, "usage: %s <thread_count>\n", prog_name);
   exit(0);
}  /* Usage */

/*------------------------------------------------------------------
 * Function:    Read_matrix
 * Purpose:     Read in the matrix
 * In args:     prompt, m, n
 * Out arg:     A
 */
void Read_matrix(char* prompt, double A[], int m, int n) {
   int             i, j;

   printf("%s\n", prompt);
   for (i = 0; i < m; i++)
      for (j = 0; j < n; j++)
         scanf("%lf", &A[i*n+j]);
}  /* Read_matrix */


/*------------------------------------------------------------------
 * Function:        Read_vector
 * Purpose:         Read in the vector x
 * In arg:          prompt, n
 * Out arg:         x
 */
void Read_vector(char* prompt, double x[], int n) {
   int   i;

   printf("%s\n", prompt);
   for (i = 0; i < n; i++)
```

Pthreads matrix-vector multiplication

```
/*------------------------------------------------------------------
 * Function:       Pth_mat_vect
 * Purpose:        Multiply an mxn matrix by an nx1 column vector
 * In arg:         rank
 * Global in vars: A, x, m, n, thread_count
 * Global out var: y
 */
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*n+j]*x[j];
   }

   return NULL;
}  /* Pth_mat_vect */


/*------------------------------------------------------------------
 * Function:    Print_matrix
 * Purpose:     Print the matrix
 * In args:     title, A, m, n
 */
void Print_matrix( char* title, double A[], int m, int n) {
   int   i, j;

   printf("%s\n", title);
   for (i = 0; i < m; i++) {
      for (j = 0; j < n; j++)
         printf("%4.1f ", A[i*n + j]);
      printf("\n");
   }
```

Compiling and Running Pth_Mat_Vec on tuckoo

```
[mthomas@tuckoo pacheco/ch4]  mthomas% gcc -g -Wall -o pth_mat_vect pth_mat_vect.c -lpthread
[mthomas@tuckoo pacheco/ch4]  mthomas% ./pth_mat_vect 4
Enter m and n
4 4
Enter the matrix
1 2 3 4
5 6 7 8
9 10 11 12
1 2 3 4
We read
 1.0  2.0  3.0  4.0
 5.0  6.0  7.0  8.0
 9.0 10.0 11.0 12.0
 1.0  2.0  3.0  4.0
Enter the vector
9 7 6 3
We read
 9.0  7.0  6.0  3.0
The product is
53.0 153.0 253.0 53.0
```

Matrix Mult Example

- More Straightforward because of shared memory
- Code only *reads* shared arrays (A, x), so no contention associated with shared updates of same memory location
- No thread communication
- Small jobs, small memory

Next we'll look at what happens when multiple threads need to update same memory location

Critical Sections

- Matrix-vector multiplication was straightforward to code:
  - Shared-memory locations were accessed in a simple manner.
  - After initialization, all of the variables but y are read only.
  - After initialization, shared variables not changed.
- Threads make changes to y: but elements are owned by a thread.
- There are *no* attempts by multiple threads to modify the *same* element.
- What happens if this is not the case? What happens when multiple threads update a single memory location?

Estimating π using n terms of A Maclaurin series: Serial Code

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

```
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;
```

See: https://www.math.hmc.edu/funfacts/ffiles/30001.1-3.shtml

POSIX Threads: Pacheco *pthd_pi.c*

First attempt:

- Parallelize similar to the way we did matrix-vector multiplication:
- Divide iterates in the *for* loop and make *sum* a shared variable.

```
*------------------------------------------------------------------
 * Function:       Thread_sum,   Purpose: Add in the terms computed by the thread running this
 * In arg:         rank
 * Ret val:        ignored
 * Globals in:     n, thread_count
 * Global in/out:  sum
 */
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i, my_n = n/thread_count, my_first_i = my_n*my_rank, 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)
      sum += factor/(2*i+1);

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

Program run with 2 threads, dual core processor

	n			
	10^5	10^6	10^7	10^8
π	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

- For two threads, as $n \uparrow$ accuracy of $\pi \uparrow$
- But, as # threads $\uparrow$ accuracy of $\pi \downarrow$

This Leads to 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

Fundamental problem with Pthreads: when multiple threads try to access/update the same resource, the result can be unpredictable.

POSIX Threads: Pacheco *pthd_pi.c* (1)

```
/* File:     pth_pi.c
 * Purpose:  Try to estimate pi using the formula:
  *         pi = 4*[1 - 1/3 + 1/5 - 1/7 + 1/9 - . . . ]
 *
 * Compile:  gcc -g -Wall -o pth_pi pth_pi.c -lm -lpthread
 * Run:      ./pth_pi <number of threads> <n>
 *           n is the number of terms of the series to use.
 *           n should be evenly divisible by the number of threads
 * Input:    none
 * Output:   Estimate of pi as computed by multiple threads, estimate
 *           as computed by one thread, and 4*arctan(1).
 * Notes:
 *    1.  The radius of convergence for the series is only 1.  So the  series converges quite slowly.
 *    2.  This version will not get right answer bcs all threads are trying to update sum!!!!
 *   Function needs a critical section to control update.
 * IPP:   Section 4.4 (pp. 162 and ff.)
 */
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <pthread.h>

const int MAX_THREADS = 1024;

long thread_count;
long long n;
double sum;

void* Thread_sum(void* rank);

/* Only executed by main thread */
void Get_args(int argc, char* argv[]);
void Usage(char* prog_name);
double Serial_pi(long long n);
```

POSIX Threads: Pacheco *pthd_pi.c* (2)

```
int main(int argc, char* argv[]) {
   long       thread;  /* Use long in case of a 64-bit system */
   pthread_t* thread_handles;
   double     sersum;
   double piref=3.14159265358979323846264;

   /* Get number of threads from command line */
   Get_args(argc, argv);

   thread_handles = (pthread_t*) malloc (thread_count*sizeof(pthread_t));
   sum = 0.0;

   for (thread = 0; thread < thread_count; thread++)
      pthread_create(&thread_handles[thread], NULL,
          Thread_sum, (void*)thread);

   for (thread = 0; thread < thread_count; thread++)
      pthread_join(thread_handles[thread], NULL);

   sum = 4.0*sum;
   printf("With n = %lld terms,\n", n);
   printf(" Reference value for pi = %.15f\n", piref);
   printf(" Pthread estimate of pi = %.15f\n", sum);
   printf("   Pthread error for pi = %.15f\n", fabs(piref - sum) );
   sersum = Serial_pi(n);
   printf("     Single thread est  = %.15f\n", sersum);
   printf("  Single Thd err for pi = %.15f\n", fabs(piref - sersum) );

   free(thread_handles);
   return 0;
   free(thread_handles);
   return 0;
}  /* main */
```

POSIX Threads: Pacheco *pthd_pi.c* (3)

```
*-------------------------------------------------------------------
 * Function:       Thread_sum,   Purpose: Add in the terms computed by the thread running this
 * In arg:         rank
 * Ret val:        ignored
 * Globals in:     n, thread_count
 * Global in/out:  sum
 */
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i, my_n = n/thread_count, my_first_i = my_n*my_rank, 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)
      sum += factor/(2*i+1);

   return NULL;
}  /* Thread_sum */

/*-------------------------------------------------------------------
 * Function:   Serial_pi,      Purpose:    Estimate pi using 1 thread
 * In arg:     n
 * Return val: Estimate of pi using n terms of Maclaurin series
 */
double Serial_pi(long long n) {
   double sum = 0.0, factor = 1.0;
   long long i;

   for (i = 0; i < n; i++, factor = -factor)
             sum += factor/(2*i+1);

   return 4.0*sum;
}  /* Serial_pi */
```

```
[mthomas@tuckoo ch4]$ ./pth_pi 100 1000
[With n = 1000 terms,
 Reference value for pi = 3.141592653589793
 Pthread estimate of pi = 3.140592653839794
   Pthread error for pi = 0.000999999749999
     Single thread est  = 3.140592653839794
  Single Thd err for pi = 0.000999999749999
```

```
[mthomas@tuckoo ch4]$ ./pth_pi 100 10000
With n = 10000 terms,
 Reference value for pi = 3.141592653589793
 Pthread estimate of pi = 3.141492653590034
   Pthread error for pi = 0.000099999999759
     Single thread est  = 3.141492653590034
  Single Thd err for pi = 0.000099999999759
```

```
[mthomas@tuckoo ch4]$ ./pth_pi 100 100000
With n = 100000 terms,
 Reference value for pi = 3.141592653589793
 Pthread estimate of pi = 3.142916601214706
   Pthread error for pi = 0.001323947624913   ----------------------->>>>>>>>  error increasing
     Single thread est  = 3.141582653589720
  Single Thd err for pi = 0.000010000000073
```

```
[mthomas@tuckoo ch4]$ ./pth_pi 100 1000000
With n = 1000000 terms,
 Reference value for pi = 3.141592653589793
 Pthread estimate of pi = 3.004711135456170
   Pthread error for pi = 0.136881518133623
     Single thread est  = 3.141591653589774
  Single Thd err for pi = 0.000001000000019
```

```
mthomas@tuckoo ch4]$ ./pth_pi 100 10000000
With n = 10000000 terms,
 Reference value for pi = 3.141592653589793
 Pthread estimate of pi = -0.028399192093270
   Pthread error for pi = 3.169991845683063
     Single thread est  = 3.141592553589792
  Single Thd err for pi = 0.000000100000002
```