DTS202TC Foundation of Parallel Computing

Lecture 3

Hong-Bin Liu
Xi'an Jiaotong-Liverpool University

September 20, 2021

Recall from last time

Xi'an Jiaotong-Liverpool University 西交利物浦大学

- Designing parallel program.
- Distributed-memory programming with MPI

Some common problems

```
Sorry!  You were supposed to get help about:
    regex:invalid-name
from the file:
    help-regex.txt
But I couldn't find that topic in the file.  Sorry!
```

Chinese character in the Computer name

```
--------------------------------------------------------------------------
Sorry!  You were supposed to get help about:
    agent-not-found
from the file:
    help-plm-rsh.txt
But I couldn't find that topic in the file.  Sorry!
--------------------------------------------------------------------------
```

Missing openssh

Some common problems

/cygdrive/d/xue/DTS202/F-hello

```
$ mpiexec -n 5 ./hello
--------------------------------------------------------------------------
There are not enough slots available in the system to satisfy the 5
slots that were requested by the application:

  ./hello

Either request fewer slots for your application, or make more slots
available for use.

A "slot" is the Open MPI term for an allocatable unit where we can
launch a process.  The number of slots available are defined by the
environment in which Open MPI processes are run:

  1. Hostfile, via "slots=N" clauses (N defaults to number of
     processor cores if not provided)
  2. The --host command line parameter, via a ":N" suffix on the
     hostname (N defaults to 1 if not provided)
  3. Resource manager (e.g., SLURM, PBS/Torque, LSF, etc.)
  4. If none of a hostfile, the --host command line parameter, or an
     RM is present, Open MPI defaults to the number of processor cores

In all the above cases, if you want Open MPI to default to the number
of hardware threads instead of the number of processor cores, use the
```

Some common questions

output_data_p, even if it's just NULL.

4. Point-to-point communications are matched on the basis of tags and communicators. Collective communications don't use tags, so they're matched solely on the basis of the communicator and the *order* in which they're called. As an example, consider the calls to `MPI_Reduce` shown in Table 3.3. Suppose that each process calls `MPI_Reduce` with operator `MPI_SUM`, and destination process 0. At first glance, it might seem that after the two calls to `MPI_Reduce`, the value of `b` will be three, and the value of `d` will be six. However, the names of the memory locations are irrelevant to the matching, of the calls to `MPI_Reduce`. The *order* of the calls will determine the matching, so the value stored in `b` will be $1+2+1=4$, and the value stored in `d` will be $2+1+2=5$.

Table 3.3 Multiple Calls to `MPI_Reduce`

Time	Process 0	Process 1	Process 2
0	`a = 1; c = 2`	`a = 1; c = 2`	`a = 1; c = 2`
1	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`
2	`MPI_Reduce(&c, &d, ...)`	`MPI_Reduce(&a, &b, ...)`	`MPI_Reduce(&c, &d, ...)`

Administration

Xi'an Jiaotong-Liverpool University 西交利物浦大学

- Assessment groups have been released.
- Decision is final.

Download Excel Sheet

Goals for this week

- Profiling tools
- Share-memory programming with Pthreads.

Outline

- Profiling Tools
- Pthreads
    - Background
    - Pthreads Basics
        - Our First Pthreads Program
        - Fundamental Concepts and Common Functions
    - Matrix-Vector Multiplication
    - Critical Sections and Synchronization
        - Critical Sections
        - Busy-Waiting
        - Mutex
        - Semaphore
        - Barrier and Condition Variables
    - Thread Safety

Profiling tools (profilers)

Wikipedia: Profiling is a form of dynamic program analysis that measures, for example, the space (memory) or time complexity of a program, the usage of particular instructions, or the frequency and duration of function calls. Most commonly, profiling information serves to aid program optimization, and more specifically, performance engineering.

- Gprof, Xcode Instruments
- mpiP
- HPCToolkit, caliper

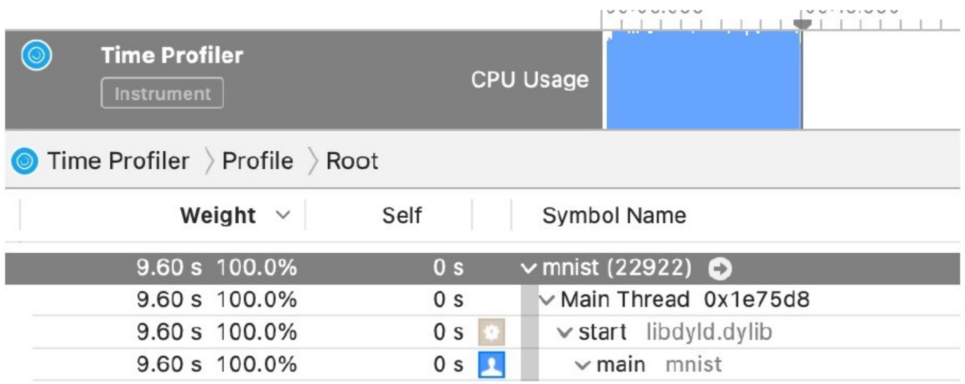


Figure 1: Instruments on Mac

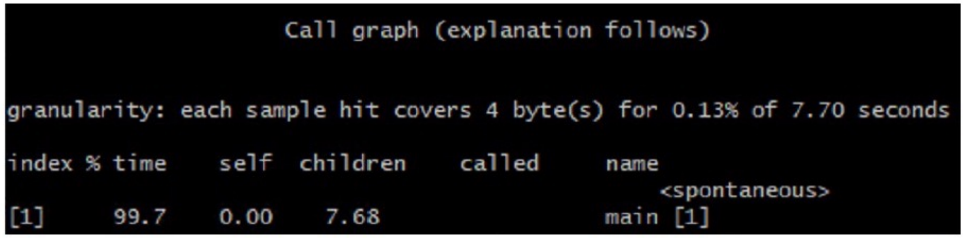


Figure 2: gprof on Cygwin Windows

Gprof Tutorial

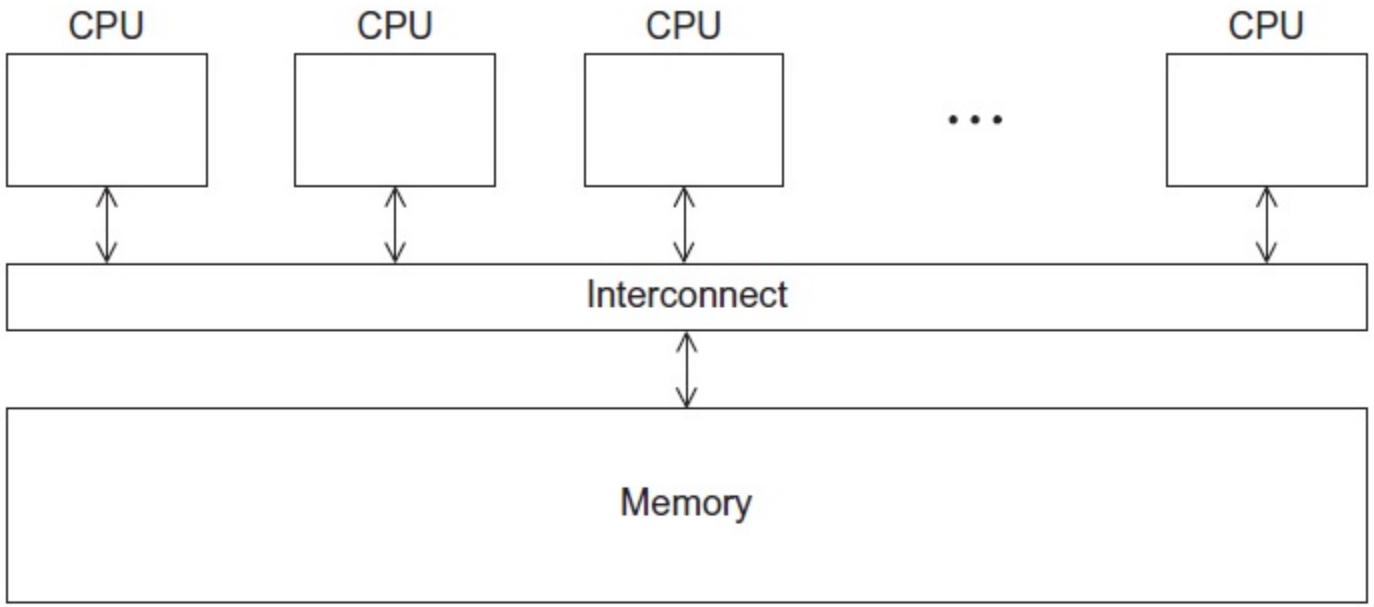
https://www.thegeekstuff.com/2012/08/gprof-tutorial/

Outline - Pthreads

Xi'an Jiaotong-Liverpool University 西交利物浦大学

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
- Thread Safety

A Shared Memory System



Threads and Processes

- In shared-memory programming, a thread is an instance of a running (or suspended) program.
- Threads are analogous to a "light-weight" process.
- In a shared-memory program, a single process may have multiple threads of control.

POSIX® Threads(Pthreads)

- IEEE had a POSIX 1003 group that defined an interface to multithreaded programming
  - This is called Pthreads
  - A standard for Unix-like operating systems. The Pthreads API is only available on POSIX systems, however, we are using Cygwin on Windows.
  - A library that can be linked with C programs.
  - Provides primitives for thread management and synchronization
- Threads are peers, no parent/child relationship

Outline

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
- Thread Safety

Hello World!

Xi'an Jiaotong-Liverpool University 西交利物浦大学

declares the various Pthreads functions, constants, types, etc.

global variable

```
#include <stdio.h>
#include <stdlib.h>
#include <pthread.h>

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

void *Hello(void* rank);  /* Thread function */

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

   /* Get number of threads from command line */
   thread_count = strtol(argv[1], NULL, 10);

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

Hello World! Cont.

Create and start new threads

Join threads

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

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

   return NULL;
}  /* Hello */
```

Compiling a Pthread program


```
gcc −g −Wall −o pth_hello pth_hello . c −lpthread
```

link in the Pthreads library

Running a Pthreads program

. /pth_hello <number of threads>

. /pth_hello 1

Hello from the main thread
Hello from thread 0 of 1

. /pth_hello 4

Hello from the main thread
Hello from thread 0 of 4
Hello from thread 1 of 4
Hello from thread 2 of 4
Hello from thread 3 of 4

Global variables

- thread_count
- Can introduce subtle and confusing bugs!
- Limit use of global variables to situations in which they're really needed.
  - Shared variables.

Outline

Starting the Threads

- Processes in MPI are usually started by a script.
- In Pthreads, the threads are started by the program executable.
  - Include code to explicitly start the threads
  - Need data structures to store threads information

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 */ ) ;
```

The function creates and starts a new thread.

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 <u>before</u> 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.

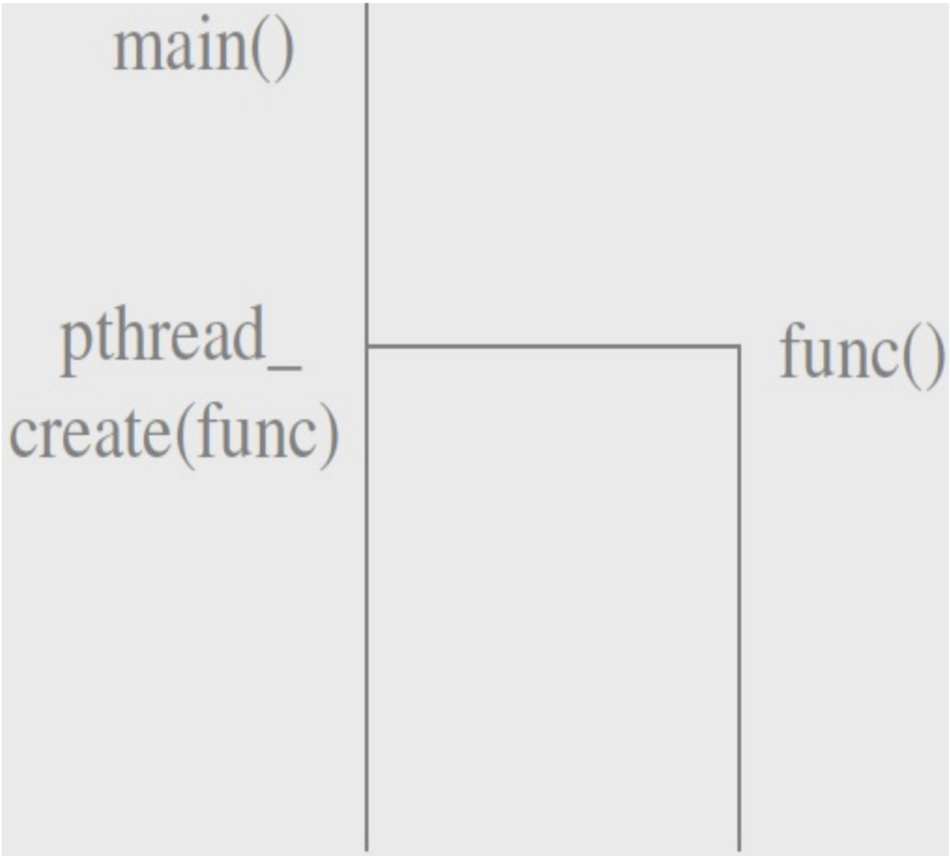
The function that the thread is to run.

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.

Example of Thread Creation

```
void *func(void *arg) {
int *i=arg;
…..
}
void main()
{
int X; pthread_t id;
….
pthread_create(&id, NULL,
                        func, &X);
…
}
```



Pthread Termination

void pthread_exit(void *status)

- Terminates the currently running thread.

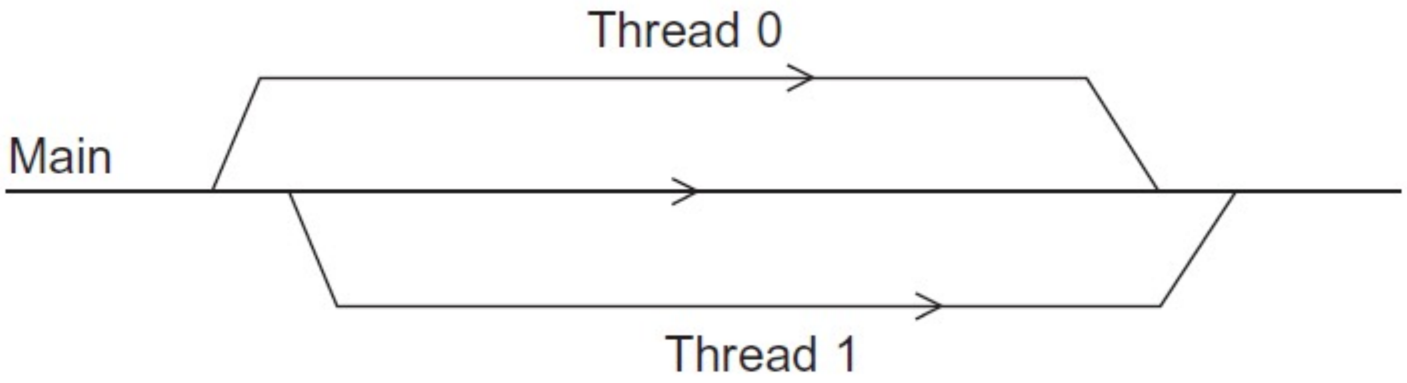
Stopping the Threads

- We call the function pthread_join once for each thread.
- int pthread_join(pthread_t new_id, /* in */
  void ** ret_val_p /* out */)
  - Waits for the thread with identifier new_id to terminate, either by returning or by calling pthread_exit()
- A single call to pthread_join will wait for the thread associated with the pthread_t object to complete.

Thread Joining Example

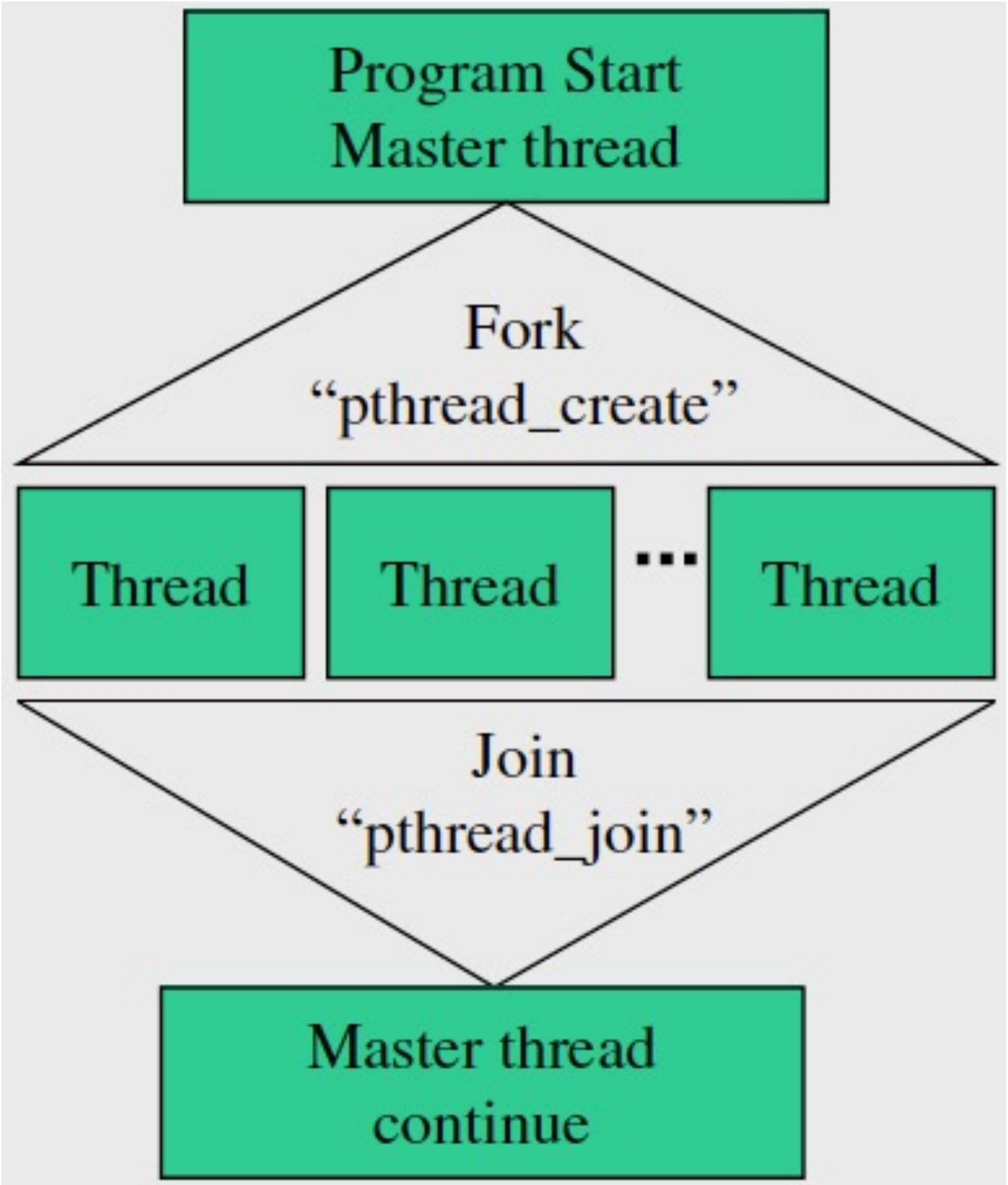

```
void *func(void *) { ….. }
pthread_t id; int X;
pthread_create(&id, NULL, func, &X);
…..
pthread_join(id, NULL);
…..
```

Running the Threads



Main thread forks and joins two threads.

Pthreads Programming Model



Pthread ID


```
pthread_t pthread_self(void);
```

- To determine the thread ID of the calling thread

Outline

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
- Thread Safety

Matrix-vector Multiplication

$$
\begin{array}{|c|c|c|c|}
\hline
a_{00} & a_{01} & \cdots & a_{0,n-1} \\
\hline
a_{10} & a_{11} & \cdots & a_{1,n-1} \\
\hline
\vdots & \vdots & & \vdots \\
\hline
a_{i0} & a_{i1} & \cdots & a_{i,n-1} \\
\hline
\vdots & \vdots & & \vdots \\
\hline
a_{m-1,0} & a_{m-1,1} & \cdots & a_{m-1,n-1} \\
\hline
\end{array}
\quad
\begin{array}{|c|}
\hline
x_0 \\
x_1 \\
\vdots \\
x_{n-1} \\
\hline
\end{array}
=
\begin{array}{|c|}
\hline
y_0 \\
\hline
y_1 \\
\hline
\vdots \\
\hline
y_i = a_{i0}x_0 + a_{i1}x_1 + \cdots a_{i,n-1}x_{n-1} \\
\hline
\vdots \\
\hline
y_{m-1} \\
\hline
\end{array}
$$

FIGURE 3.11

Matrix-vector multiplication

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

Serial Pseudo-code

Xi'an Jiaotong-Liverpool University 西交利物浦大学

```
/* 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];
}
```

Using Three 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

Xi'an Jiaotong-Liverpool University 西交利物浦大学

```
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 */
```

Outline

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
- Thread Safety

Data Race in Pthreads Program


```
static int s = 0;
```

```
Thread 1

  for i = 0, n/2-1
      s = s + f(A[i])
```

```
Thread 2

  for i = n/2, n-1
      s = s + f(A[i])
```

- Problem is a race condition on variable s in the program

- When multiple threads attempt to access a shared resource, at least one of the accesses is an update, and the accesses can result in an error, we have a race condition .

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;
```

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 */
```

Using a 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

- Note that as we increase n, the estimate with one thread gets better and better.
- However, for larger values of n , the result computed by two threads actually gets worse.
- It matters if multiple threads try to update a single shared variable.

Possible race condition


```
y = Compute(my rank);
x = x + y;
```

y: private, x: shared, initialized to 0

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`

A race condition or data race occurs when:

- Two processors (or two threads) access the same variable, and at least one does a write.
- The accesses are concurrent (not synchronized) so they could happen simultaneously.

Critical Sections

- Critical Section is a block of code that updates a shared resources that can only be updated by one thread a time.

Outline

Xi'an Jiaotong-Liverpool University 西交利物浦大学

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
  - Read-Write Locks
- Thread Safety

Pthreads Synchronization

- Create/exit/join
  - provide some form of synchronization,
  - at a very coarse level,
  - requires thread creation/destruction.
- Need for finer-grain synchronization
  - mutex locks
  - condition variables
  - ....
- PTHREADS provides a variety of synchronization facilities for threads to cooperate in accessing shared resources.

Busy-Waiting


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

flag initialized to 0 by main thread

- Busy-waiting is not an ideal solution to the problem of controlling access to a critical section.
- Since thread 1 will execute the test over and over until thread 0 executes flag++ , if thread 0 is delayed, thread 1 will simply "spin" on the test, eating up CPU cycles. This can be positively disastrous for performance.

Busy-Waiting

- A thread repeatedly tests a condition, but, effectively, does no useful work until the condition has the appropriate value.
- The busy-wait solution would work "provided the statements are executed exactly as they're written."
- Beware of optimizing compilers, though!

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

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

- Turning off compiler optimizations can seriously degrade performance.

Pthreads Global Sum with Busy-waiting

Xi'an Jiaotong-Liverpool University 西交利物浦大学

```
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 */
```

When $n=10^8$, the serial sum is consistently faster than the parallel sum.

Global Sum Function with Critical Section after Loop

Xi'an Jiaotong-Liverpool University 西交利物浦大学

```
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;

   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 */
```

Outline

Xi'an Jiaotong-Liverpool University
西交利物浦大学

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
  - Read-Write Locks
- Thread Safety

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

Mutexes

- The Pthreads standard includes a special type for mutexes: pthread_mutex_t. Need to be initialized by the system before it's used.

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

- Creates a new mutex lock.
- Attribute: normal, recursive, errorcheck

(Igonre the second argument in this book, just pass NULL.)

Mutexes

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

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

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

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

  - Tries to acquire the lock specified by mutex.
  - If mutex is already locked, then calling thread blocks until mutex is unlocked.

Mutexes

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

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

  - If calling thread has mutex currently locked, this will unlock the mutex.
  - If other threads are blocked waiting on this mutex, one will unblock and acquire mutex, which one is determined by the scheduler.

Global Sum Function that Uses a Mutex

Xi'an Jiaotong-Liverpool University 西交利物浦大学

```
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;

   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 */
```

Outline

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
  - Read-Write Locks
- Thread Safety

Some Issues

- Busy-waiting enforces the order threads access a critical section.
- Using mutexes, the order is left to chance and the system.
- There are applications where we need to control the order threads access the critical section.

Problems with a Mutex Solution


```
/* n and product_matrix are shared and initialized by the main
thread */
/* product_matrix is initialized to be the identity matrix  */

void* Thread_work(void* rank) {
   long my_rank = (long) rank;
   matrix_t my_mat = Allocate_matrix(n);
   Generate_matrix(my_mat);
   pthread_mutex_lock(&mutex);
   Multiply_matrix(product_mat, my_mat);
   pthread_mutex_unlock(&mutex);
   Free_matrix(&my_mat);
   return NULL;
}  /* Thread_work */
```

A First Attempt at Sending Messages Using Pthreads


```c
/* messages has type char**. It's allocated in main. */
/* Each entry is set to NULL in main.                 */
void *Send_msg(void* rank) {
   long my_rank = (long) rank;
   long dest = (my_rank + 1) % thread_count;
   long source = (my_rank + thread_count − 1) % thread_count;
   char* my_msg = malloc(MSG_MAX*sizeof(char));

   sprintf(my_msg, "Hello to %ld from %ld", dest, my_rank);
   messages[dest] = my_msg;

   if (messages[my_rank] != NULL)
      printf("Thread %ld > %s\n", my_rank, messages[my_rank]);
   else
      printf("Thread %ld > No message from %ld\n", my_rank, source);

   return NULL;
}  /* Send_msg */
```

No receiving message for multithreads

Possible Solutions with Problems

S1: Change if statement to while statement:

```
–if (messages[my_rank] != NULL)
        printf("Thread %ld  > %s\n", my_rank, messages[my_rank]);
–while (messages[my_rank] = NULL);
        printf("Thread %ld  > %s\n", my_rank, messages[my_rank]);
```

- However, there is a busy-waiting problem.

- S2: Mutex Lock:

```
...
Pthread_mutex_lock(mutex[dest]);
...
Messages[dest]=msg;
Pthread_mutex_unlock(mutex[dest]);
...
Pthread_mutex_lock(mutex[myrank]);
printf("Thread %ld  > %s\n", my_rank, messages[my_rank]);
...
```

- However, it still will crash.

Semaphore

- Semaphores can be thought of as a special type of unsigned int , so they can take on the values 0, 1, 2, ... When they take on the values 0 and 1, called a binary semaphore.
- For binary semaphore, 0 corresponds to a locked mutex, and 1 corresponds to an unlocked mutex.
  - Initialized to 1(unlocked).
  - Before the critical, call sem_wait . Executing sem_wait will block if the semaphore is 0. If the semaphore is nonzero, it will decrement the semaphore and proceed.
  - After executing the critical, call sem_post , which increments the semaphore, and a thread waiting in sem_wait can proceed.

Syntax of the Various Semaphore Functions

Semaphores are not part of Pthreads; you need to add this.

```
#include <semaphore.h>
```

Initialize the semaphore descriptor.

```
int sem_init(
      sem_t*      semaphore_p    /* out */,
      int         shared         /* in  */,
      unsigned    initial_val    /* in  */);
```

Unlock a semaphore.

Destroy a semaphore.

```
int sem_destroy(sem_t*   semaphore_p   /* in/out */);
int sem_post(sem_t*      semaphore_p   /* in/out */);
int sem_wait(sem_t*      semaphore_p   /* in/out */);
```

Lock a semaphore.

Send Messages Using Semaphores

Xi'an Jiaotong-Liverpool University
西交利物浦大学

```
/* messages is allocated and initialized to NULL in main   */
/* semaphores is allocated and initialized to 0 (locked) in
      main */
void* Send_msg(void* rank) {
   long my_rank = (long) rank;
   long dest = (my_rank + 1) % thread_count;
   char* my_msg = malloc(MSG_MAX*sizeof(char));

   sprintf(my_msg, "Hello to %ld from %ld", dest, my_rank);
   messages[dest] = my_msg;
   sem_post(&semaphores[dest])
         /* ''Unlock'' the semaphore of dest */

   /* Wait for our semaphore to be unlocked */
   sem_wait(&semaphores[my_rank]);
   printf("Thread %ld > %s\n", my_rank, messages[my_rank]);

   return NULL;
}  /* Send_msg */
```

- The message-sending problem didn't involve a critical section.
- Thread my_rank couldn't proceed until thread source had finished creating the message.
- When a thread can't proceed until another thread has taken some action, is sometimes called producer-consumer synchronization.

Outline

Xi'an Jiaotong-Liverpool University 西交利物浦大学

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
- Thread Safety

Barriers

- Synchronizing the threads to make sure that they all are at the same point in a program is called a barrier.

- No thread can cross the barrier until all the threads have reached it.

Using Barriers to Time the Slowest Thread


```
/* Shared */
double elapsed_time;
. . .
/* Private */
double my_start, my_finish, my_elapsed;
. . .
Synchronize threads;
Store current time in my_start;
/* Execute timed code */
. . .
Store current time in my_finish;
my_elapsed = my_finish - my_start;

elapsed = Maximum of my_elapsed values;
```

Using Barriers for Debugging


```
point in program we want to reach;
barrier;
if (my_rank == 0) {
   printf("All threads reached this point\n");
   fflush(stdout);
}
```

Busy-waiting and a Mutex

- Implementing a barrier using busy-waiting and a mutex is straightforward.
- We use a shared counter protected by the mutex.
- When the counter indicates that every thread has entered the critical section, threads can leave the busy-wait loop.

Busy-waiting and a Mutex

Xi'an Jiaotong-Liverpool University 西交利物浦大学

```
/* Shared and initialized by the main thread */
int counter;  /* Initialize to 0 */
int thread_count;
pthread_mutex_t barrier_mutex;
. . .

void* Thread_work(. . .) {
    . . .
    /* Barrier */
    pthread_mutex_lock(&barrier_mutex);
    counter++;
    pthread_mutex_unlock(&barrier_mutex);
    while (counter < thread_count);
    . . .
}
```

We need one counter variable for each instance of the barrier, otherwise problems are likely to occur.

Implementing a Barrier with Semaphores

protects the counter

```
/* Shared variables */
int counter;          /* Initialize to 0 */
sem_t count_sem;      /* Initialize to 1 */
sem_t barrier_sem;    /* Initialize to 0 */
. . .
void* Thread_work(...) {
   . . .
   /* Barrier */
   sem_wait(&count_sem);
   if (counter == thread_count-1) {
      counter = 0;
      sem_post(&count_sem);
      for (j = 0; j < thread_count-1; j++)
         sem_post(&barrier_sem);
   } else {
      counter++;
      sem_post(&count_sem);
      sem_wait(&barrier_sem);
   }
   . . .
```

block threads that have entered the barrier

Reusing barrier_sem results in a race condition.

Condition Variables

- A condition variable is a data object that allows a thread to suspend execution until a certain event or condition occurs.
- When the event or condition occurs, another thread can signal the thread to "wake up."
- A condition variable is always associated with a mutex.

Condition Variables


```
lock mutex;
if condition has occurred
   signal thread(s);
else {
   unlock the mutex and block;
   /* when thread is unblocked, mutex is relocked */
}
unlock mutex;
```

Condition Variables

- Condition variables in Pthreads have type pthread_cond_t.

```
int pthread_cond_init(
      pthread_cond_t*            cond_p       /* out */,
      const pthread_condattr_t*  cond_attr_p  /* in  */);
```

- Creates a new condition variable cond.
- Attribute: ignore for now.

```
int pthread_cond_destroy(pthread_cond_t*  cond_p  /* in/out */);
```

- Destroys the condition variable cond.

Condition Variables


```
int pthread_cond_signal(pthread_cond_t*  cond_var_p /* in/out */);
```

- Unblock one of the blocked threads waiting on cond.
- Which one is determined by scheduler.
- If no thread waiting, then signal is a no-op.

```
int pthread_cond_broadcast(pthread_cond_t* cond_var_p /* in/out */);
```

- Unblock all of the blocked threads waiting on cond.
- If no thread waiting, then signal is a no-op.

Condition Variables


```
int pthread_cond_wait(
      pthread_cond_t*     cond_var_p    /* in/out */,
      pthread_mutex_t*    mutex_p       /* in/out */);
```

- Blocks the calling thread, waiting on cond.
- Unlocks the mutex.

```
pthread_mutex_unlock(&mutex_p);
wait_on_signal(&cond_var_p);
pthread_mutex_lock(&mutex_p);
```

Implementing a Barrier with Condition Variables


```
/* Shared */
int counter = 0;
pthread_mutex_t mutex;
pthread_cond_t cond_var;
. . .
void* Thread_work(. . .) {
   . . .
   /* Barrier */
   pthread_mutex_lock(&mutex);
   counter++;
   if (counter == thread_count) {
      counter = 0;
      pthread_cond_broadcast(&cond_var);
   } else {
      while (pthread_cond_wait(&cond_var, &mutex) != 0);
   }
   pthread_mutex_unlock(&mutex);
   . . .
}
```

Outline

- Background
- Pthreads Basics
  - Our First Pthreads Program
  - Fundamental Concepts and Common Functions
- Matrix-Vector Multiplication
- Critical Sections and Synchronization
  - Critical Sections
  - Busy-Waiting
  - Mutex
  - Semaphore
  - Barrier and Condition Variables
  - Read-Write Locks
- Thread Safety

Thread-Safety

- A block of code is thread-safe if it can be simultaneously executed by multiple threads without causing problems.

Example

- Suppose we want to use multiple threads to "tokenize" a file that consists of ordinary English text.
- The tokens are just contiguous sequences of characters separated from the rest of the text by white-space — a space, a tab, or a newline.

Simple Approach

- Divide the input file into lines of text and assign the lines to the threads in a round-robin fashion.
- The first line goes to thread 0, the second goes to thread 1, . . . , the tth goes to thread t, the t +1st goes to thread 0, etc.
- We can serialize access to the lines of input using semaphores.
- After a thread has read a single line of input, it can tokenize the line using the strtok function.

The Strtok Function


```
char* strtok(
      char*          string      /* in/out */,
      const char*    separators  /* in     */);
```

- The idea is that in the first call, strtok caches a pointer to string, and for subsequent calls it returns successive tokens taken from the cached copy.
- The first time it's called the string argument should be the text to be tokenized.(One line of input.)
- For subsequent calls, the first argument should be NULL.

Multi-threaded Tokenizer


```
void* Tokenize(void* rank) {
   long my_rank = (long) rank;
   int count;
   int next = (my_rank + 1) % thread_count;
   char *fg_rv;
   char my_line[MAX];
   char *my_string;

   sem_wait(&sems[my_rank]);
   fg_rv = fgets(my_line, MAX, stdin);
   sem_post(&sems[next]);
   while (fg_rv != NULL) {
      printf("Thread %ld > my line = %s", my_rank, my_line);

      count = 0;
      my_string = strtok(my_line, " \t\n");
      while ( my_string != NULL ) {
         count++;
         printf("Thread %ld > string %d = %s\n", my_rank, count,
               my_string);
         my_string = strtok(NULL, " \t\n");
      }

      sem_wait(&sems[my_rank]);
      fg_rv = fgets(my_line, MAX, stdin);
      sem_post(&sems[next]);
   }

   return NULL;
}  /* Tokenize */
```

Running with One Thread

- It correctly tokenizes the input stream.

Pease porridge hot.
Pease porridge cold.
Pease porridge in the pot
Nine days old.

Running with Two Threads


```
Thread 0 > my line = Pease porridge hot.
Thread 0 > string 1 = Pease
Thread 0 > string 2 = porridge
Thread 0 > string 3 = hot.
Thread 1 > my line = Pease porridge cold.
Thread 0 > my line = Pease porridge in the pot
Thread 0 > string 1 = Pease
Thread 0 > string 2 = porridge
Thread 0 > string 3 = in
Thread 0 > string 4 = the
Thread 0 > string 5 = pot
Thread 1 > string 1 = Pease
Thread 1 > my line = Nine days old.
Thread 1 > string 1 = Nine
Thread 1 > string 2 = days
Thread 1 > string 3 = old.
```

Oops!

What happened?

- strtok caches the input line by declaring a variable to have static storage class.
- This causes the value stored in this variable to persist from one call to the next.
- Unfortunately for us, this cached string is shared, not private.
- Thus, thread 0's call to strtok with the third line of the input has apparently overwritten the contents of thread 1's call with the second line.
- So the strtok function is not thread-safe. If multiple threads call it simultaneously, the output may not be correct.

Other Unsafe C Library Functions

- Regrettably, it's not uncommon for C library functions to fail to be thread-safe.
- The random number generator random in stdlib.h.
- The time conversion function localtime in time.h.

“re-entrant”(Thread Safe) Functions

- In some cases, the C standard specifies an alternate, thread-safe, version of a function.

```
char* strtok_r(
      char*          string       /* in/out */,
      const char*    separators,  /* in     */
      char**         saveptr_p    /* in/out */);
```

Caveat

Incorrect programs can produce correct output!

Summary