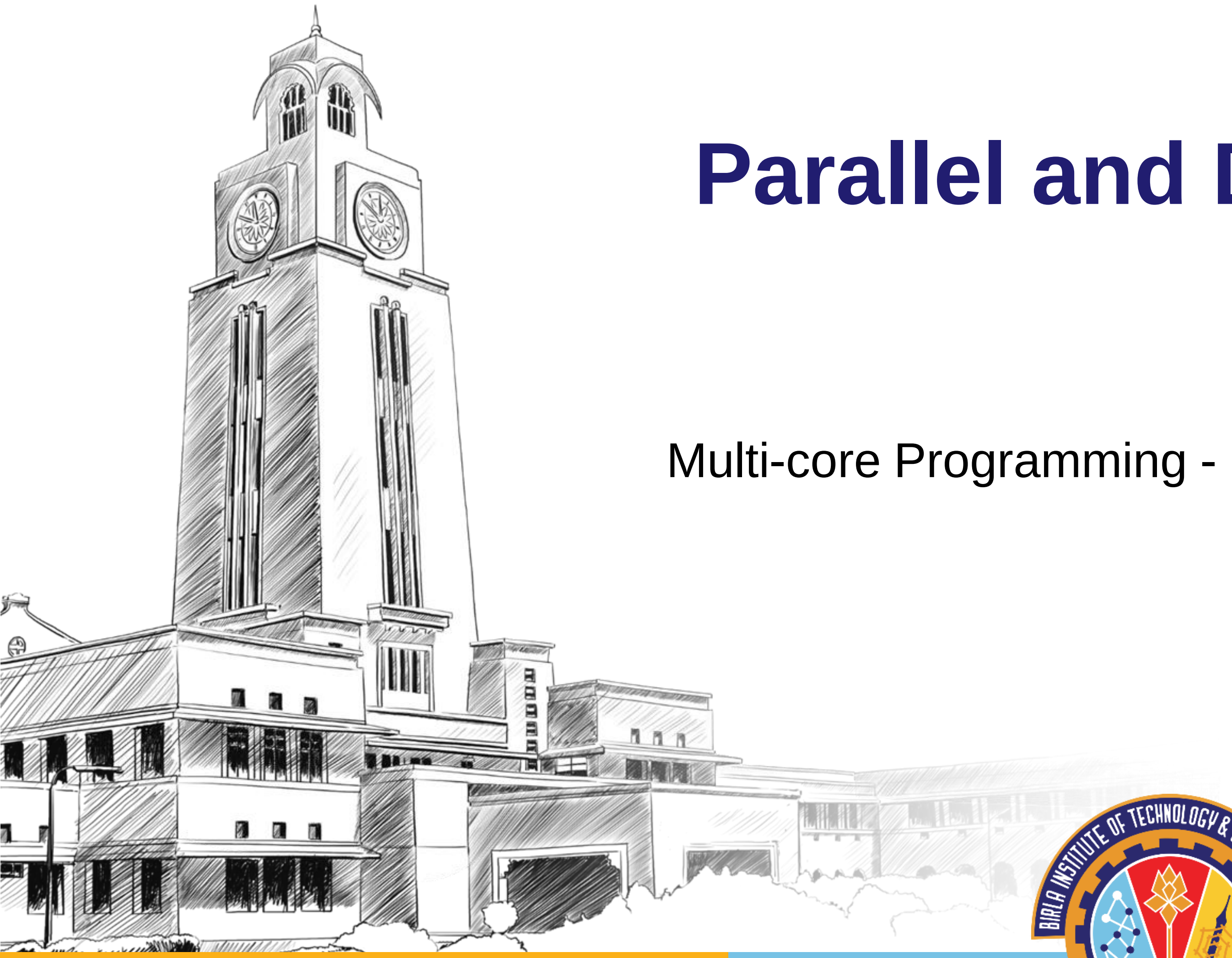


Introduction to
Parallel and Distributed Programming

CS5
Multi-core Programming - PThreads

Saikishor Jangiti

Agenda

- Lab 3
- Problems programming shared memory systems.
- Controlling access to a critical section.
- Thread synchronisation.
- Programming with POSIX threads.
- Mutexes.
- Producer-consumer synchronisation and semaphores.
- Barriers and condition variables.
- Read-write locks.
- Thread safety.

Lab 3

- **Enhance performance using multithreading within one node**

Use multithreading to improve Lab 2 code on slave nodes. Idea is to improve performance using multiple cores on the same node and show synchronization problems/solutions.

Lab 2: Use cluster to distribute work and do some parallel data processing

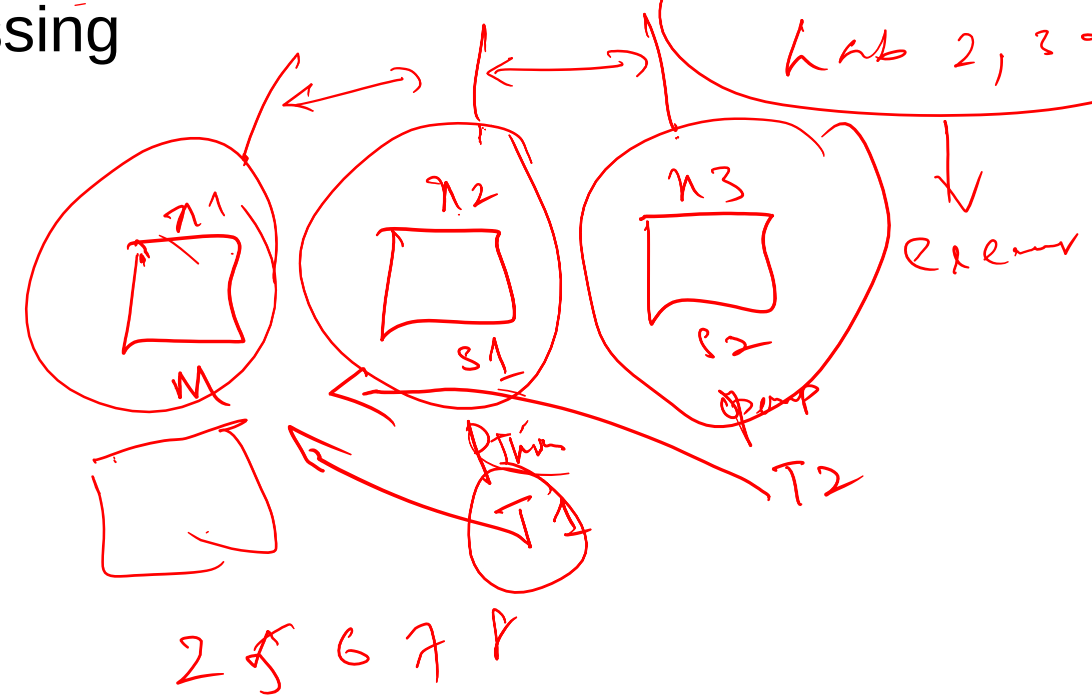
- Now that you have a group of nodes managed as a cluster
  - Create a distributed data processing capability.
  - Master node takes a dataset and distributes / partitions the data on multiple active slaves that have enough resources.
  - Slaves process the data and send results back to Master. Master merges / reduces the data and reports back to the user.
  - Use blocking vs non-blocking messages in OpenMPI.
  - Status of the work at slaves is reported back to the master as work progresses and finishes.
  - Master collects the performance data (CPU, mem, IO) and stores it for analysis.
  - Any errors are also reported to the master.
  - Use compression to transfer data. Quantify communication cost - bytes sent over the network, latency of transfer.
  - Use OpenMPI for communication between nodes, zlib etc. compression libs
  - Handle a node crash - Master should get work done on remaining nodes. What are the options - should it restart the job or only shift part of the work to another node ? How is a slave crash detected ? Use the heartbeat mechanism.

Our Goal and Where we are

E1

10 % A2

- Distributed data processing
- Parallel and distributed
  - ➢ Programming
  - ➢ Computing
  - ➢ Processing
  - ➢ System



A2

12 + 6

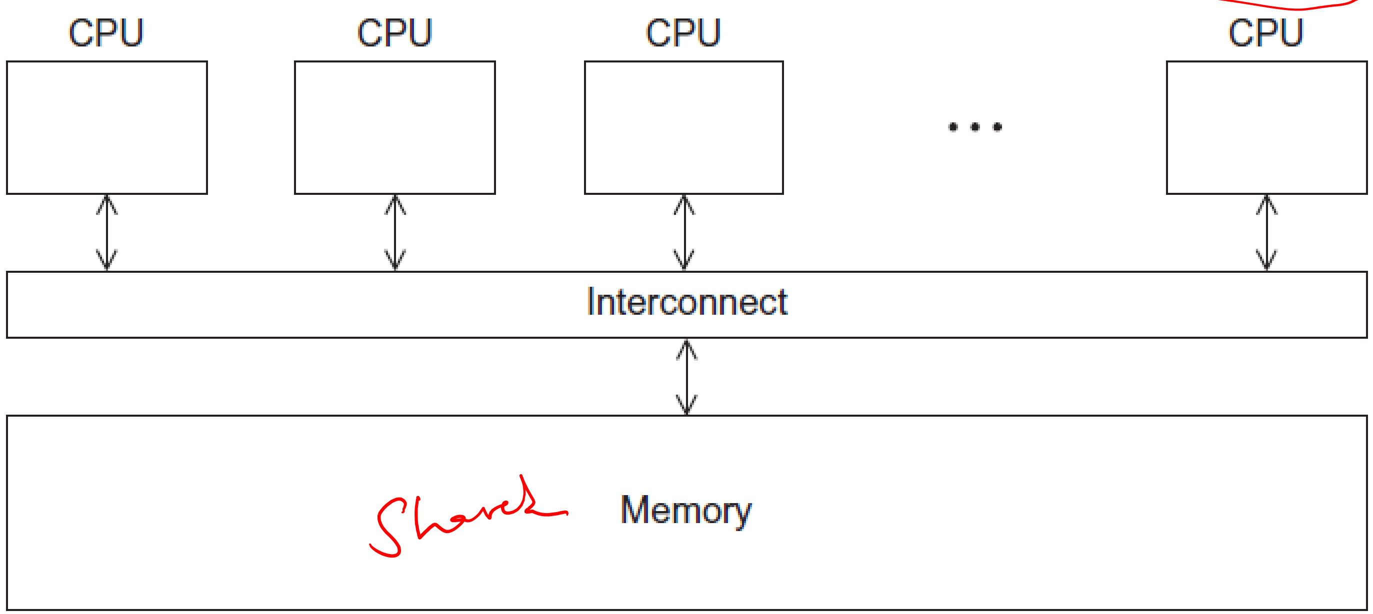
18

A3 10 8+2

A4 10 8+2

(10 1 0 1 0)

A Shared Memory System



Processes and Threads

- A process 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

- 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.

Caveat

- The Pthreads API is only available on POSIXR systems — Linux, MacOS X, Solaris, HPUX, …

C Pointers

p 2000 4800

int var; 9 2000

var=9;

int *p;

*p = var

int* p;

p = &var;

var = 9

*p = 9

var = var + 1

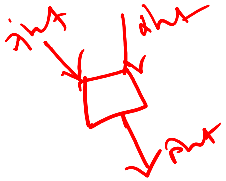
var = var + var2

```c
#include<stdio.h>

void main()
{
    int var = 9;
    int *p;
    *p=var;
    printf("Value of the variable var is: %d\n", var);
    printf("Memory address of the variable var is: %x\n", &var);
    printf("Memory address to which p is pointing : %x\n", p);
}
```

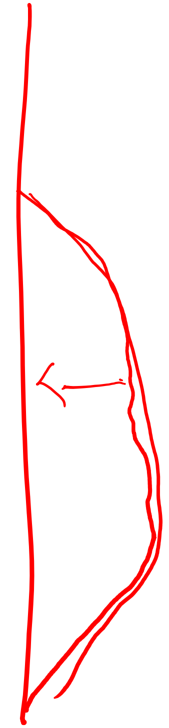
PROBLEMS 6 OUTPUT DEBUG CONSOLE TERMINAL

```
sai@BITS-Pilani:/mnt/c/Users/Sai/IPDP$ ./cpointer
Value of the variable var is: 9
Memory address of the variable var is: e66656cc
Memory address to which p is pointing : e66657d0
sai@BITS-Pilani:/mnt/c/Users/Sai/IPDP$
```

Function pointer



int *fp ('int, int)



SendRecv.c 4 | cpointer.c 2 | functionpointer.c 2 | NBServer.c

C: > Users > Sai > IPDP > functionpointer.c > main()

```c
#include<stdio.h>
#define SIZE 4
int product(int number1, int number2){    return number1*number2;}
int add(int number1, int number2){    return number1+number2; }
int subtract(int number1, int number2) {    return number1-number2; }
int division(int number1, int number2) {    return number1/number2; }
int main()
{ int number1=10, number2 = 5;
// declare an array of function pointers
    int (*func_ptr_arr[SIZE])(int, int);
// assign the functions to function pointers.
    func_ptr_arr[0] = add;
    func_ptr_arr[1] = subtract;
    func_ptr_arr[2] = product;
    func_ptr_arr[3] = division;
    // Iterate over the array of function pointers
for(int i=0; i<SIZE; i++) {int res = (*func_ptr_arr[i])(number1, number2 );
                            printf("%d\n", res);    }
return 0;
}
```

PROBLEMS 8 | OUTPUT | DEBUG CONSOLE | TERMINAL

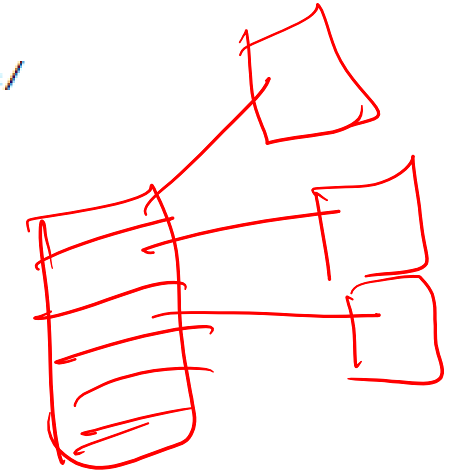
```
sai@BITS-Pilani:/mnt/c/Users/Sai/IPDP$ ./a.out
15
5
50
2
```

Hello World! (1)

```c
#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));
```

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

Void Ptr



Hello World! (2)

```
    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 */
```

Hello World! (3)

```
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

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

Starting the Threads

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

Starting the Threads

pthread.h

One object for each thread.

pthread_t

```
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 <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.

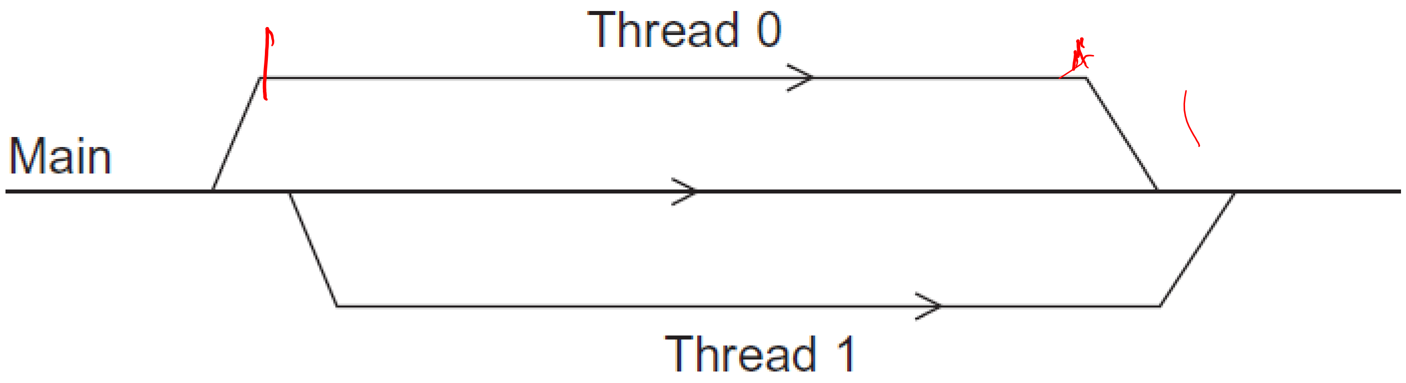
Function started by pthread_create

- 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.

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

m threads

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

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]

6 2

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

10

100 rows

1 0 - 9

2 10 - 19

10 90 - 99

```
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 */
```

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
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

[illegible] α

Safety

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 */
```

6

0

100

10^4

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

Safety

Speed

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!

GS x

```
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)

Loca

```
   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 */
```

Global

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

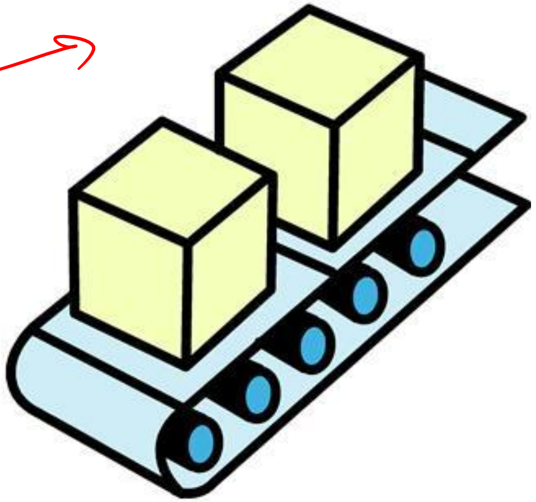
$$\frac{T_{\text{serial}}}{T_{\text{parallel}}} \approx \texttt{thread\_count}$$

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

Time	`flag`	Thread 0	Thread 1	Thread 2	Thread 3	Thread 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

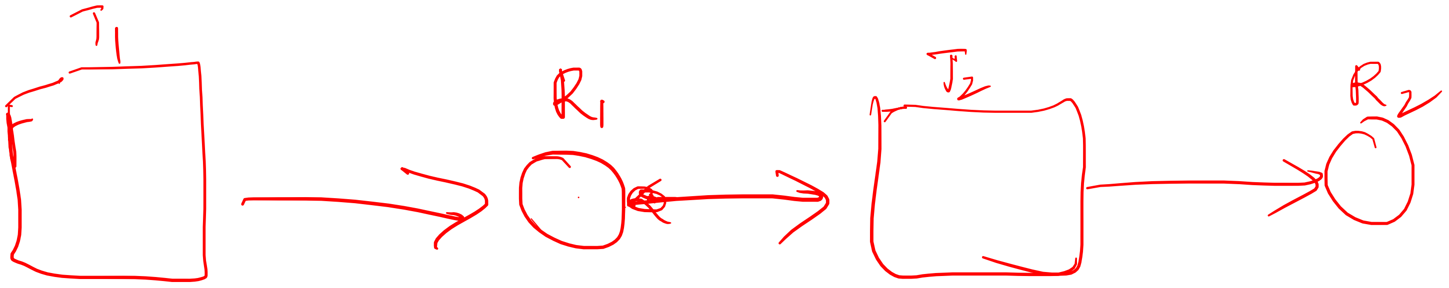
Possible sequence of events with busy-waiting and more threads than cores.

Producer-Consumer Synchronization and Semaphores



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

```
/* 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 */
```

Syntax of the various semaphore functions

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

```
#include <semaphore.h>

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

0 1 2 3 4

0, 1

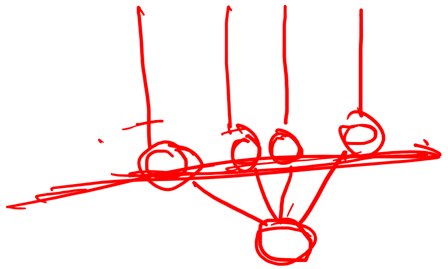
```
int sem_destroy(sem_t*  semaphore_p  /* in/out */);
int sem_post(sem_t*     semaphore_p  /* in/out */);
int sem_wait(sem_t*     semaphore_p  /* in/out */);
```

Barriers and Condition Variables

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 critical section.

Busy-waiting and a Mutex

```
/* 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

```
/* 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);
   }
   . . .
```

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;
```

Implementing a barrier with condition variables

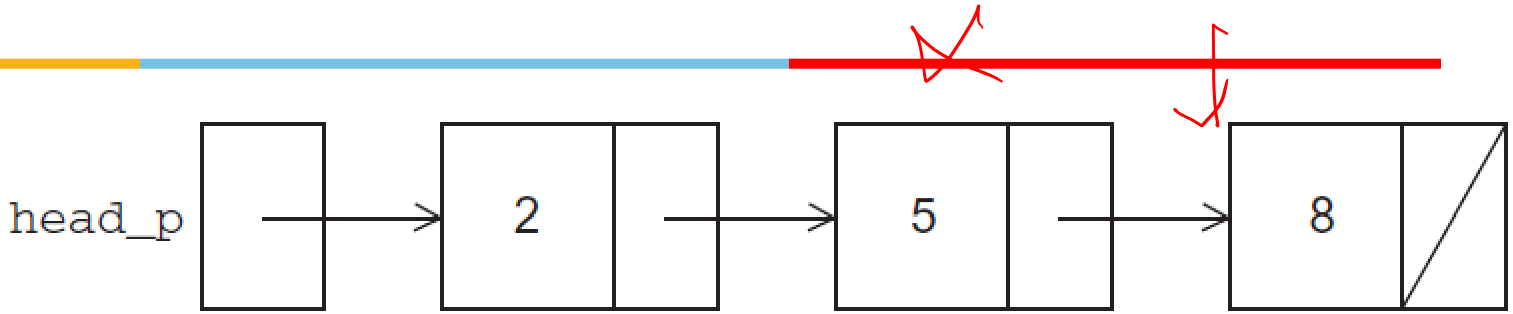
```
/* Shared */
int counter = 0;
pthread_mutex_t mutex;
pthread_cond_t cond_var;
. . .
void* Thread_work(. . .) {
    . . .
    /* Barrier */
    pthread_mutex_lock(&mutex);
    counter++;
    if (counter == thread_count) {
       counter = 0;
       pthread_cond_broadcast(&cond_var);
    } else {
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

Read-Write Locks

Controlling access to a large, shared data structure

- Let’s look at an example.
- Suppose the shared data structure is a sorted linked list of ints, and the operations of interest are Member, Insert, and Delete.

Linked Lists

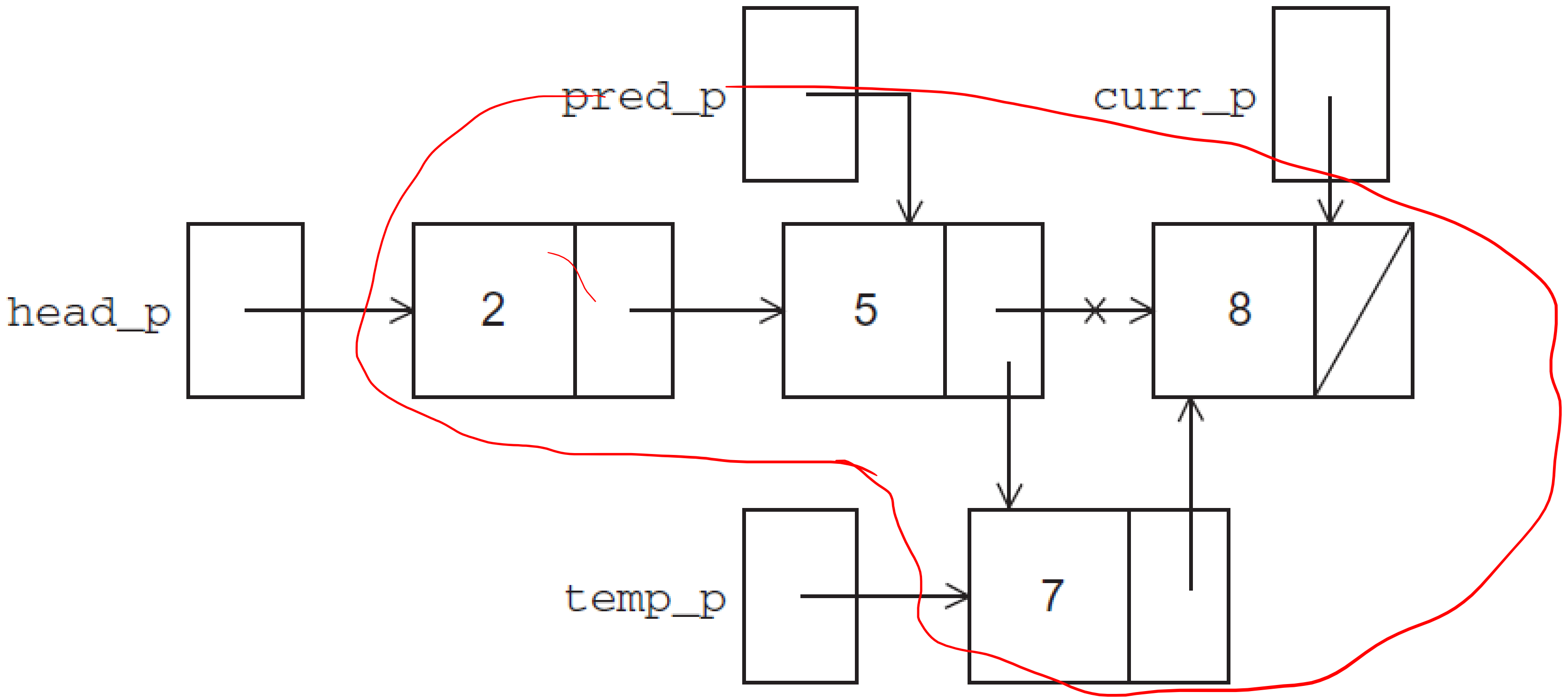



```
struct list_node_s {
    int data;
    struct list_node_s* next;
}
```

Linked List Membership

```
int  Member(int value, struct list_node_s* head_p) {
   struct list_node_s* curr_p = head_p;

   while (curr_p != NULL && curr_p->data < value)
      curr_p = curr_p->next;

   if (curr_p == NULL || curr_p->data > value) {
      return 0;
   } else {
      return 1;
   }
}  /* Member */
```

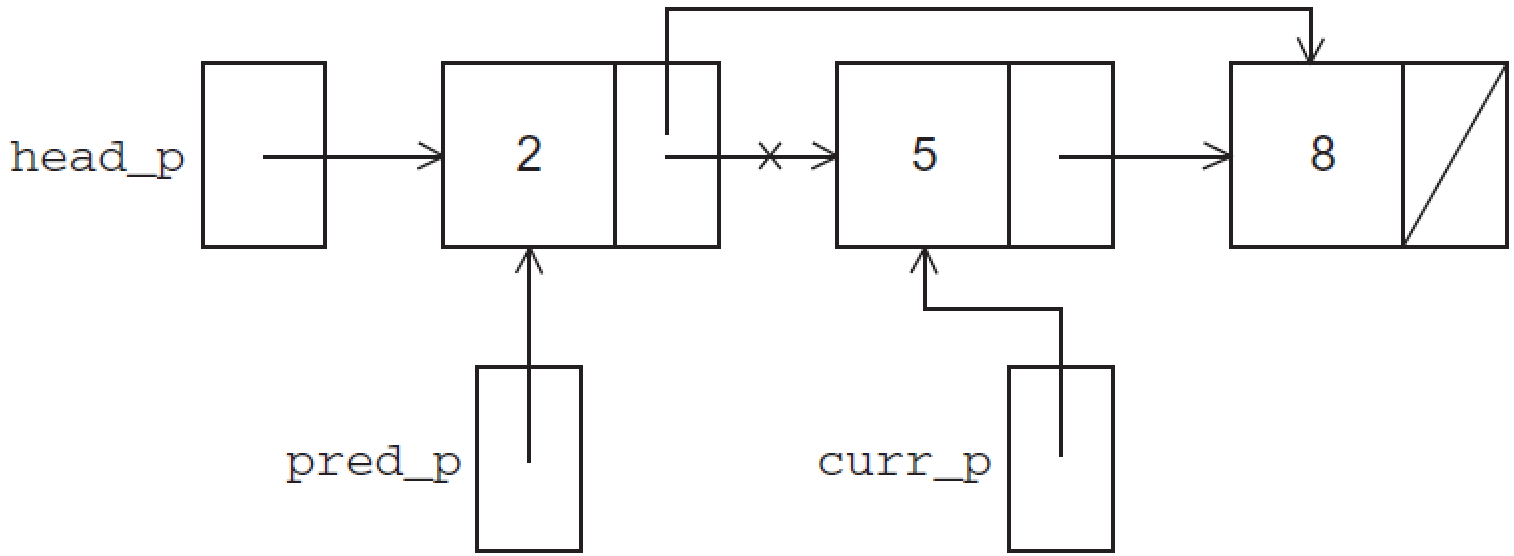
Inserting a new node into a list



Inserting a new node into a list

```
int Insert(int value, struct list_node_s** head_pp) {
   struct list_node_s* curr_p = *head_pp;
   struct list_node_s* pred_p = NULL;
   struct list_node_s* temp_p;

   while (curr_p != NULL && curr_p->data < value) {
      pred_p = curr_p;
      curr_p = curr_p->next;
   }

   if (curr_p == NULL || curr_p->data > value) {
      temp_p = malloc(sizeof(struct list_node_s));
      temp_p->data = value;
      temp_p->next = curr_p;
      if (pred_p == NULL)  /* New first node */
         *head_pp = temp_p;
      else
         pred_p->next = temp_p;
      return 1;
   } else { /* Value already in list */
      return 0;
   }
}  /* Insert */
```

Deleting a node from a linked list



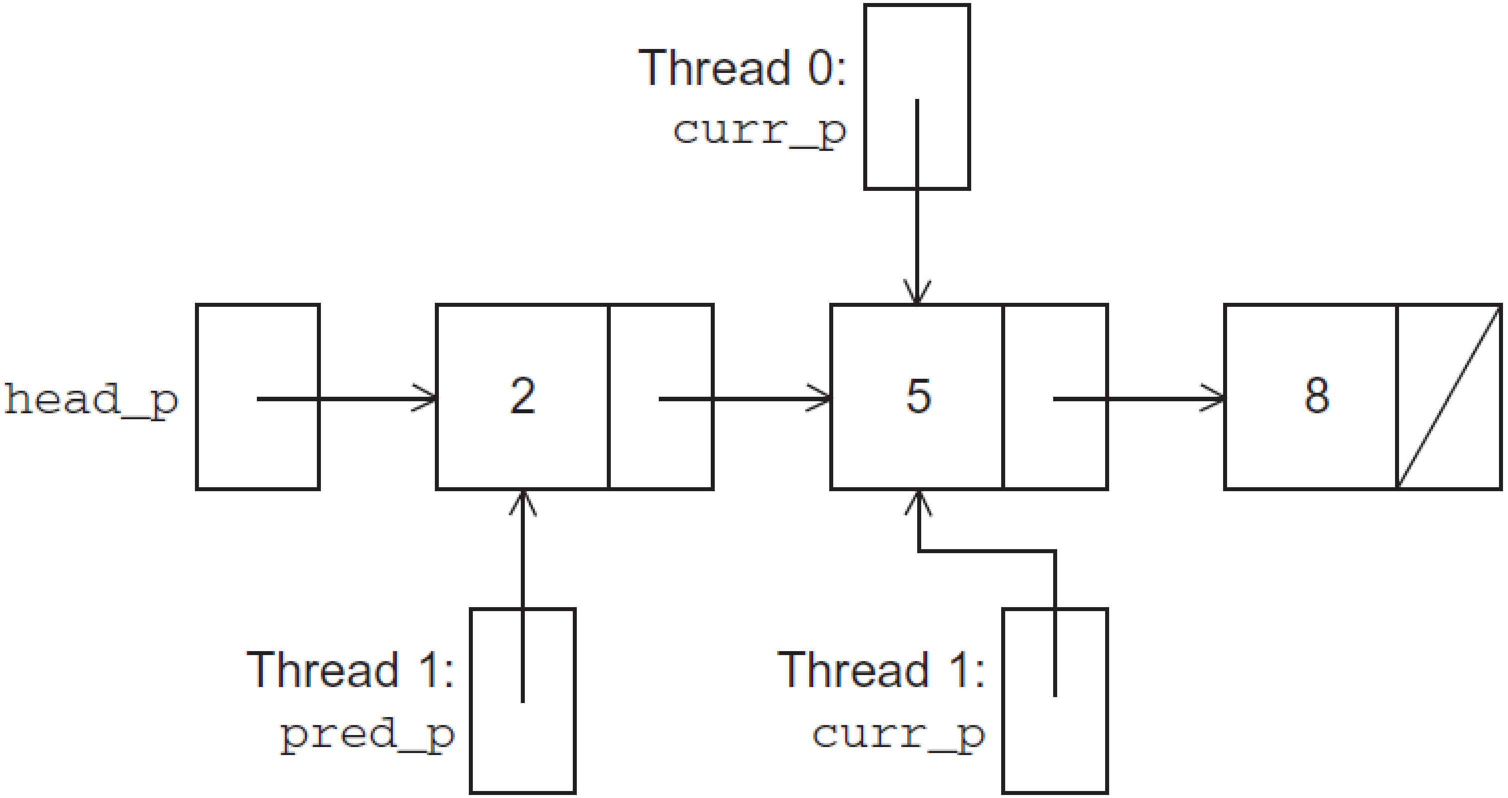
Deleting a node from a linked list

```
int Delete(int value, struct list_node_s** head_pp) {
   struct list_node_s* curr_p = *head_pp;
   struct list_node_s* pred_p = NULL;

   while (curr_p != NULL && curr_p->data < value) {
      pred_p = curr_p;
      curr_p = curr_p->next;
   }

   if (curr_p != NULL && curr_p->data == value) {
      if (pred_p == NULL) { /* Deleting first node in list */
         *head_pp = curr_p->next;
         free(curr_p);
      } else {
         pred_p->next = curr_p->next;
         free(curr_p);
      }
      return 1;
   } else { /* Value isn't in list */
      return 0;
   }
}  /* Delete */
```

A Multi-Threaded Linked List

- Let’s try to use these functions in a Pthreads program.
- In order to share access to the list, we can define head_p to be a global variable.
- This will simplify the function headers for Member, Insert, and Delete, since we won’t need to pass in either head_p or a pointer to head_p: we’ll only need to pass in the value of interest.

Simultaneous access by two threads



Solution #1

- An obvious solution is to simply lock the list any time that a thread attempts to access it.
- A call to each of the three functions can be protected by a mutex.

```
Pthread_mutex_lock(&list_mutex);
Member(value);
Pthread_mutex_unlock(&list_mutex);
```

In place of calling Member(value).

Issues

- We’re serializing access to the list.
- If the vast majority of our operations are calls to Member, we’ll fail to exploit this opportunity for parallelism.
- On the other hand, if most of our operations are calls to Insert and Delete, then this may be the best solution since we’ll need to serialize access to the list for most of the operations, and this solution will certainly be easy to implement.

Solution #2

- Instead of locking the entire list, we could try to lock individual nodes.
- A “finer-grained” approach.

```
struct list_node_s {
    int data;
    struct list_node_s* next;
    pthread_mutex_t mutex;
}
```

Issues

- This is much more complex than the original Member function.
- It is also much slower, since, in general, each time a node is accessed, a mutex must be locked and unlocked.
- The addition of a mutex field to each node will substantially increase the amount of storage needed for the list.

Implementation of Member with one mutex per list node (1)

```
int  Member(int value) {
   struct list_node_s* temp_p;

   pthread_mutex_lock(&head_p_mutex);
   temp_p = head_p;
   while (temp_p != NULL && temp_p->data < value) {
      if (temp_p->next != NULL)
         pthread_mutex_lock(&(temp_p->next->mutex));
      if (temp_p == head_p)
         pthread_mutex_unlock(&head_p_mutex);
      pthread_mutex_unlock(&(temp_p->mutex));
      temp_p = temp_p->next;
   }
```

Implementation of Member with one mutex per list node (2)

```
   if (temp_p == NULL || temp_p->data > value) {
      if (temp_p == head_p)
         pthread_mutex_unlock(&head_p_mutex);
      if (temp_p != NULL)
         pthread_mutex_unlock(&(temp_p->mutex));
      return 0;
   } else {
      if (temp_p == head_p)
         pthread_mutex_unlock(&head_p_mutex);
      pthread_mutex_unlock(&(temp_p->mutex));
      return 1;
   }
}  /* Member */
```

Pthreads Read-Write Locks

- Neither of our multi-threaded linked lists exploits the potential for simultaneous access to any node by threads that are executing Member.
- The first solution only allows one thread to access the entire list at any instant.
- The second only allows one thread to access any given node at any instant.

Pthreads Read-Write Locks

- A read-write lock is somewhat like a mutex except that it provides two lock functions.

- The first lock function locks the read-write lock for reading, while the second locks it for writing.

Pthreads Read-Write Locks

- So multiple threads can simultaneously obtain the lock by calling the read-lock function, while only one thread can obtain the lock by calling the write-lock function.

- Thus, if any threads own the lock for reading, any threads that want to obtain the lock for writing will block in the call to the write-lock function.

Pthreads Read-Write Locks

- If any thread owns the lock for writing, any threads that want to obtain the lock for reading or writing will block in their respective locking functions.

Protecting our linked list functions

```
pthread_rwlock_rdlock(&rwlock);
Member(value);
pthread_rwlock_unlock(&rwlock);
. . .
pthread_rwlock_wrlock(&rwlock);
Insert(value);
pthread_rwlock_unlock(&rwlock);
. . .
pthread_rwlock_wrlock(&rwlock);
Delete(value);
pthread_rwlock_unlock(&rwlock);
```

Linked List Performance

Implementation	Number of Threads 1	2	4	8
Read-Write Locks	0.213	0.123	0.098	0.115
One Mutex for Entire List	0.211	0.450	0.385	0.457
One Mutex per Node	1.680	5.700	3.450	2.700

100,000 ops/thread

99.9% Member

0.05% Insert

0.05% Delete

Linked List Performance

Implementation	Number of Threads 1	2	4	8
Read-Write Locks	2.48	4.97	4.69	4.71
One Mutex for Entire List	2.50	5.13	5.04	5.11
One Mutex per Node	12.00	29.60	17.00	12.00

100,000 ops/thread

80% Member

10% Insert

10% Delete

Caches, Cache-Coherence, and False Sharing

- Recall that chip designers have added blocks of relatively fast memory to processors called cache memory.
- The use of cache memory can have a huge impact on shared-memory.
- A write-miss occurs when a core tries to update a variable that's not in cache, and it has to access main memory.

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 */
```

Run-times and efficiencies of matrix-vector multiplication

Threads	Matrix Dimension					
	$8,000,000 \times 8$		8000×8000		$8 \times 8,000,000$	
	Time	Eff.	Time	Eff.	Time	Eff.
1	0.393	1.000	0.345	1.000	0.441	1.000
2	0.217	0.906	0.188	0.918	0.300	0.735
4	0.139	0.707	0.115	0.750	0.388	0.290

(times are in seconds)

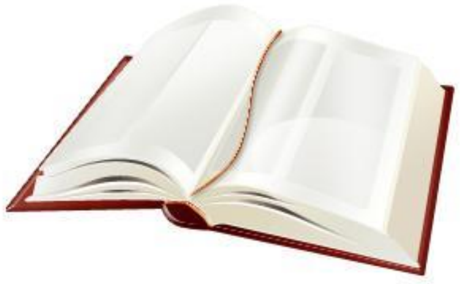
Thread-Safety

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.

Simple approach

- 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

- The first time it's called the string argument should be the text to be tokenized.
  - Our line of input.
- For subsequent calls, the first argument should be NULL.

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

The strtok function

- The idea is that in the first call, strtok caches a pointer to string, and for subsequent calls it returns successive tokens <u>taken from the cached copy</u>.

Multi-threaded tokenizer (1)

```
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);
```

Multi-threaded tokenizer (2)

```
        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.

What happened?

- Thus, thread 0’s call to strtok with the third line of the input has apparently <u>overwritten</u> 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 */);
```

Concluding Remarks (1)

- A thread in shared-memory programming is analogous to a process in distributed memory programming.
- However, a thread is often lighter-weight than a full-fledged process.
- In Pthreads programs, all the threads have access to global variables, while local variables usually are private to the thread running the function.

Concluding Remarks (2)

- When indeterminacy results from multiple threads attempting to access a shared resource such as a shared variable or a shared file, at least one of the accesses is an update, and the accesses can result in an error, we have a race condition.

Concluding Remarks (3)

- A critical section is a block of code that updates a shared resource that can only be updated by one thread at a time.
- So the execution of code in a critical section should, effectively, be executed as serial code.

Concluding Remarks (4)

- Busy-waiting can be used to avoid conflicting access to critical sections with a flag variable and a while-loop with an empty body.
- It can be very wasteful of CPU cycles.
- It can also be unreliable if compiler optimization is turned on.

Concluding Remarks (5)

- A mutex can be used to avoid conflicting access to critical sections as well.
- Think of it as a lock on a critical section, since mutexes arrange for mutually exclusive access to a critical section.

Concluding Remarks (6)

- A semaphore is the third way to avoid conflicting access to critical sections.
- It is an unsigned int together with two operations: sem_wait and sem_post.
- Semaphores are more powerful than mutexes since they can be initialized to any nonnegative value.
- A semaphore is a variable used to control access to a shared resource within the operating system, and a mutex is simply a lock acquired before entering a critical section and releasing it. **A semaphore is better for multiple instances of a resource, but a mutex is better for a single shared resource**

Concluding Remarks (7)

- A barrier is a point in a program at which the threads block until all of the threads have reached it.
- A read-write lock is used when it’s safe for multiple threads to simultaneously read a data structure, but if a thread needs to modify or write to the data structure, then only that thread can access the data structure during the modification.

Concluding Remarks (8)

- Some C functions cache data between calls by declaring variables to be static, causing errors when multiple threads call the function.
- This type of function is not thread-safe.