用Pthreads进行共享内存编程

任课教师：吴迪

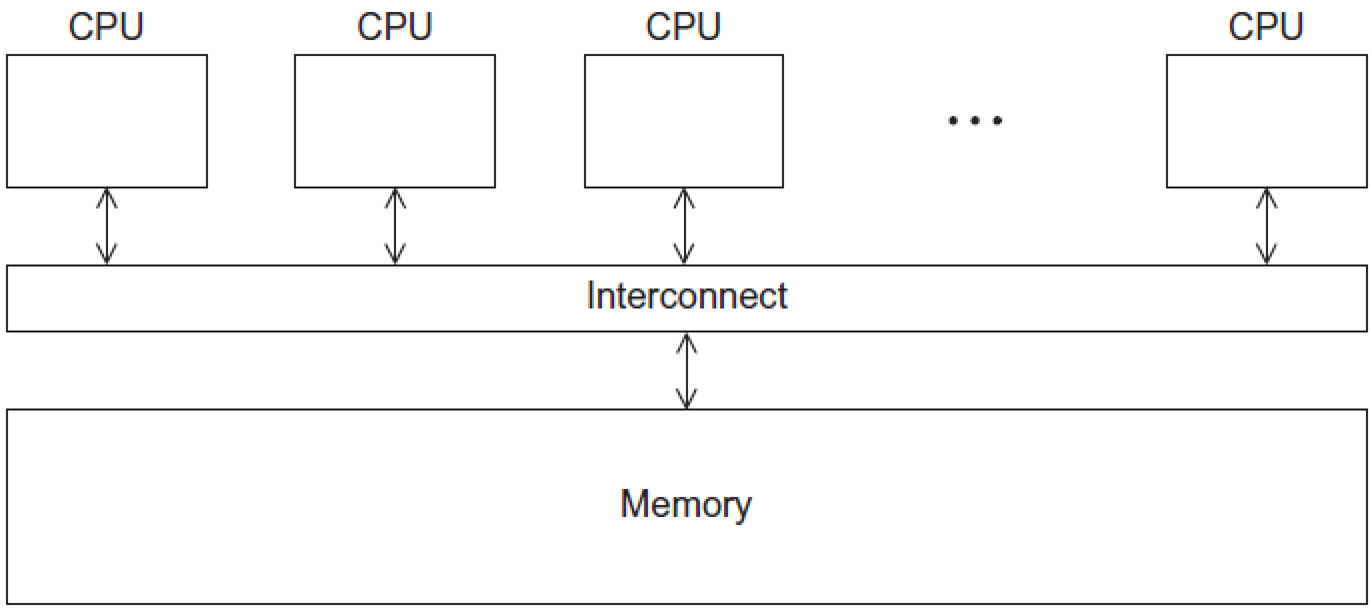
课程内容

- 参考资料：
  - 并行程序设计导论，Peter S Pacheco，机械工业出版社， 2016
  - Chapter 4 Shared-Memory Programming With Pthreads

Roadmap

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

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

- Portable Operating System Interface (POSIX)
- 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, …

Hello World! (1)

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

```
#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! (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

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 */ ) ;
```

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

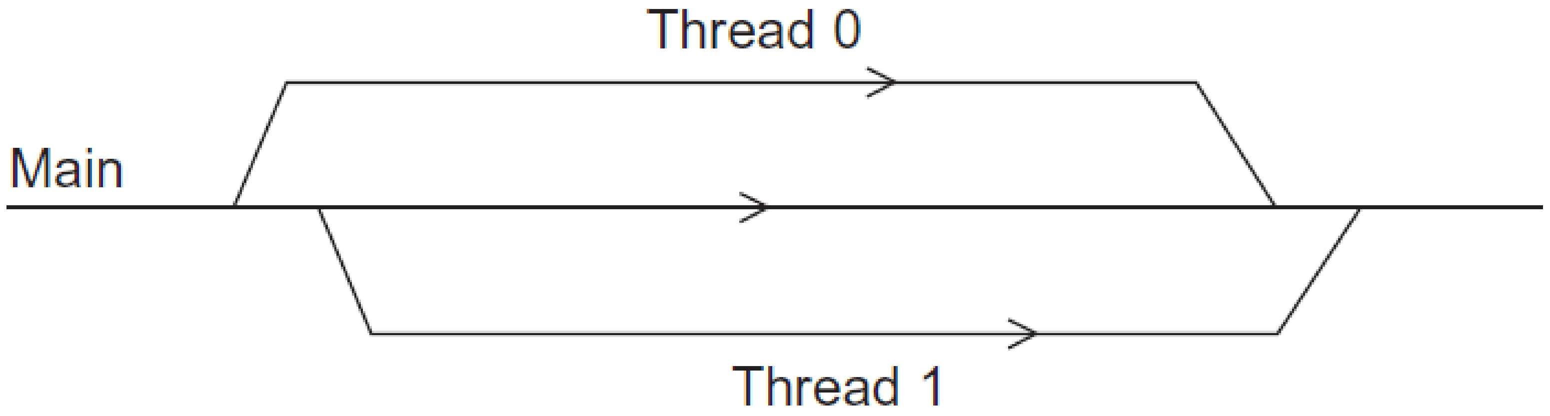
- Prototype:
  void* thread_function (void* args_p) ;

- 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.

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

Matrix-Vector Multiplication in pthreads

Serial pseudo-code

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

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

Using 3 Pthreads

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

thread 0

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

general case

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

Pthreads matrix-vector multiplication

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

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

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

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

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

A thread function for computing π

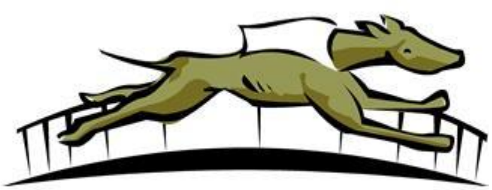
```
void* Thread_sum(void* rank) {
   long my_rank = (long) rank;
   double factor;
   long long i;
   long long my_n = n/thread_count;
   long long my_first_i = my_n*my_rank;
   long long my_last_i = my_first_i + my_n;

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

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

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

Possible race condition

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

y= compute()

x=x+y



x=1+2?

x=2?

Busy-Waiting

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

- Beware of optimizing compilers, though!

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

flag initialized to 0 by main thread

Pthreads global sum with busy-waiting

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

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

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

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

Global sum function with critical section after loop (1)

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

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

Global sum function with critical section after loop (2)

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

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

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

Mutexes

- A thread that is busy-waiting may continually use the CPU accomplishing nothing.

- **Mutex** (mutual exclusion) is a special type of variable that can be used to restrict access to a critical section to a single thread at a time.

Mutexes

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

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

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

Mutexes

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

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

- 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 */);
```

Mutexes

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

```
int pthread_mutex_destroy(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

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

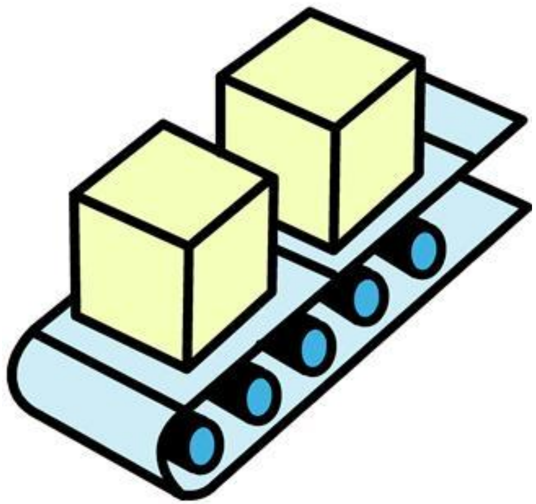
\# of threads > # of cores

Run-times (in seconds) of π programs using n = 10^8 terms on a system with two four-core processors.

5 threads   2 cores

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

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



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

```
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 */
```

Problem: matrix multiplication is not commutative

For example, $A * B * C \neq C * B * A$

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;
                                   while (messages[my_rank] == NULL);
   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 */
```

Problem: If running 2+ threads on a dual-core system, some of the messages are never received.

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  */);


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 */);
```

int sem_init(sem_t *sem,int pshared,unsigned int value);

value表示初始化信号的值

pshared为0，表示信号在当前进程的多个线程之间共享

int sem_wait(sem_t *sem);

- sem_wait可以用来阻塞当前线程，直到信号量的值大于0，解除阻塞。
- 解除阻塞后，sem的值-1，表示公共资源被执行减少了

int sem_post(sem_t *sem);

- sem_post用于增加信号量的值，信号量+1
- 当有线程阻塞在这个信号量上时，调用这个函数会使其中的一个线程不再阻塞，选择机制由线程的调度策略决定。

Using Semaphores to send msgs

semaphores[thread_count]

```
/* semaphores are initialized to 0 (locked) */
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;
}
```

```c
int main(int argc, char* argv[]) {
  long thread;
  pthread_t* thread_handles;
  messages = malloc(MSG_MAX*sizeof(char));

  if(argc != 1) Usage(argv[0]);

  thread_count = 8;
  semaphores = malloc(thread_count*sizeof(sem_t));
  sem_init(semaphores, 0, 0);

  /* allocate array for threads */
  thread_handles = malloc(thread_count*sizeof(pthread_t));

  /* start threads */
  for(thread = 0; thread < thread_count; thread++) {
    pthread_create(&thread_handles[thread], NULL, Send_msg,
             (void*) thread);
  }

  /* wait for threads to complete */
  for(thread = 0; thread < thread_count; thread++) {
    pthread_join(thread_handles[thread], NULL);
  }
```

```
ehpc@f68c2d045077:~/data$ ./4_8_pth_msg_smp
Thread 1 > Hello to 1 from 0
Thread 2 > Hello to 2 from 1
Thread 3 > Hello to 3 from 2
Thread 4 > Hello to 4 from 3
Thread 5 > Hello to 5 from 4
Thread 6 > Hello to 6 from 5
Thread 7 > Hello to 7 from 6
Thread 0 > Hello to 0 from 7
ehpc@f68c2d045077:~/data$ ./4_8_pth_msg_smp
Thread 1 > Hello to 1 from 0
Thread 2 > Hello to 2 from 1
Thread 3 > Hello to 3 from 2
Thread 4 > Hello to 4 from 3
Thread 5 > Hello to 5 from 4
Thread 7 > Hello to 7 from 6
Thread 6 > Hello to 6 from 5
Thread 0 > Hello to 0 from 7
```

输出不一定严格有序，但是消息发送的顺序是有序的

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);
   }
   . . .
```

int sem_wait(sem_t *sem);

- sem_wait可以用来阻塞当前线程，直到信号量的值大于0，解除阻塞。
- 解除阻塞后，sem的值-1，表示公共资源被执行减少了

信号量和互斥锁(mutex)的区别：

- 互斥锁只允许一个线程进入临界区，
- 而信号量允许多个线程同时进入临界区。

先判断，如果大于0，解除阻塞，减去1；

如果等于0，保持阻塞

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);
    . . .
}
```

pthread_mutex_unlock(&mutex);
wait_on_signal(&cond_var);
pthread_mutex_lock(&mutex)

通常的应用场景下，当前线程执行pthread_cond_wait时，处于临界区访问共享资源，存在一个mutex与该临界区相关联，这是理解pthread_cond_wait带有mutex参数的关键

- 当前线程执行pthread_cond_wait前，已经获得了和临界区相关联的mutex；**执行pthread_cond_wait会阻塞，但是在进入阻塞状态前，必须释放已经获得的mutex，让其它线程能够进入临界区**
- 当前线程执行pthread_cond_wait后，阻塞等待的条件满足，条件满足时会被唤醒；**被唤醒后，仍然处于临界区，因此被唤醒后必须再次获得和临界区相关联的mutex**
- 综上，调用pthread_cond_wait时，线程总是位于某个临界区，该临界区与mutex相关，pthread_cond_wait需要带有一个参数mutex，用于释放和再次获取mutex。

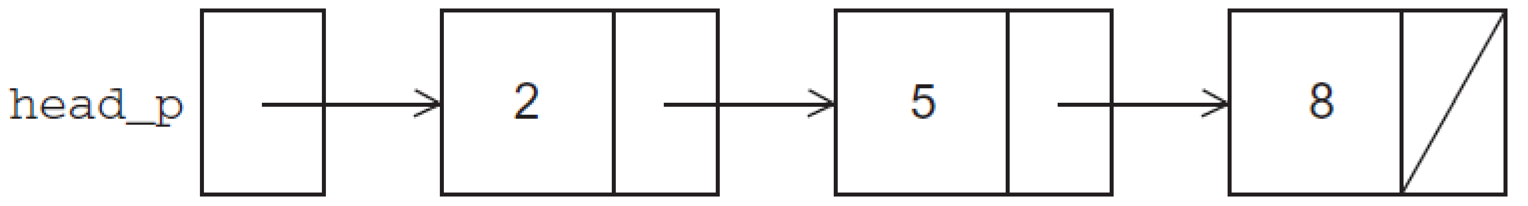
Read-Write Locks

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

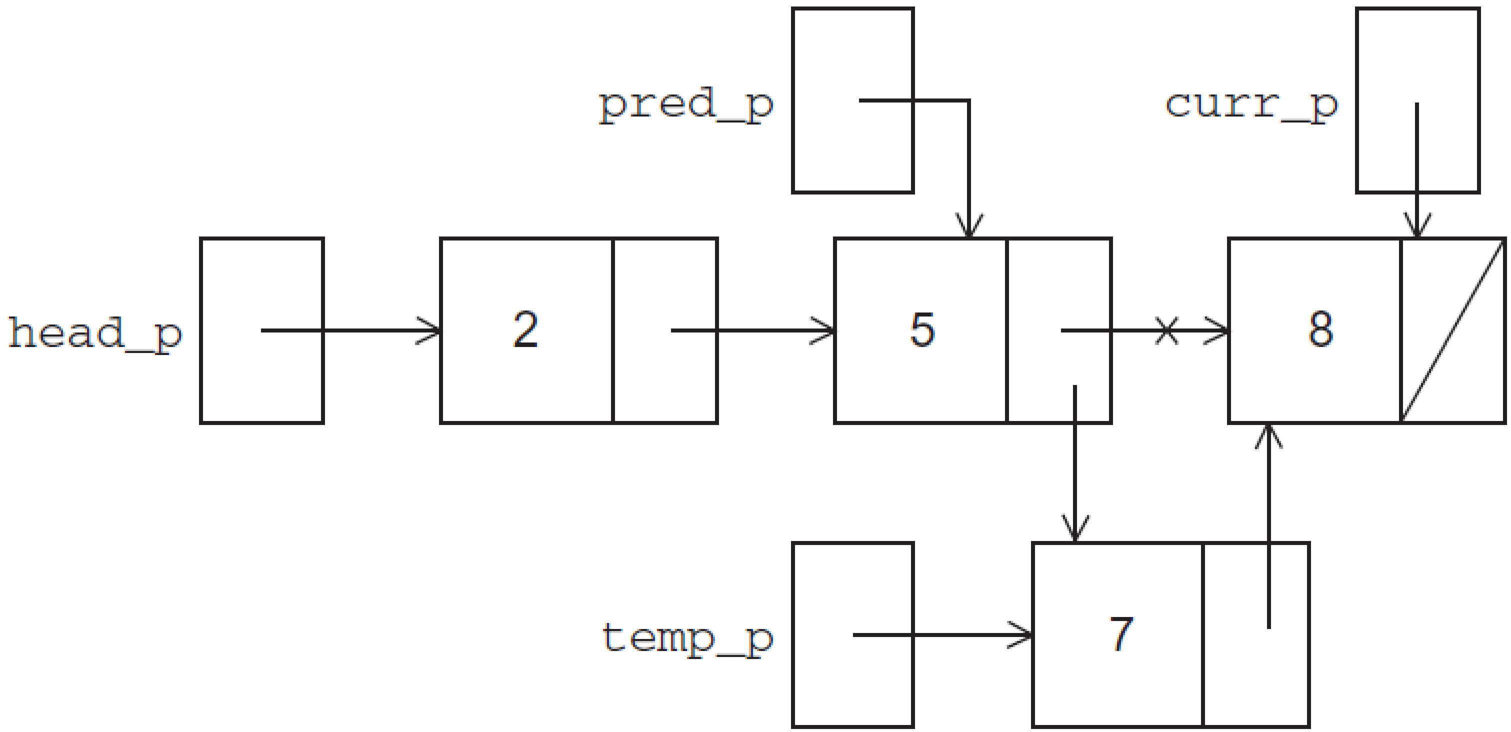



```
struct list_node_s {
    int data;
    struct list_node_s* next;
}
```

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 */
```

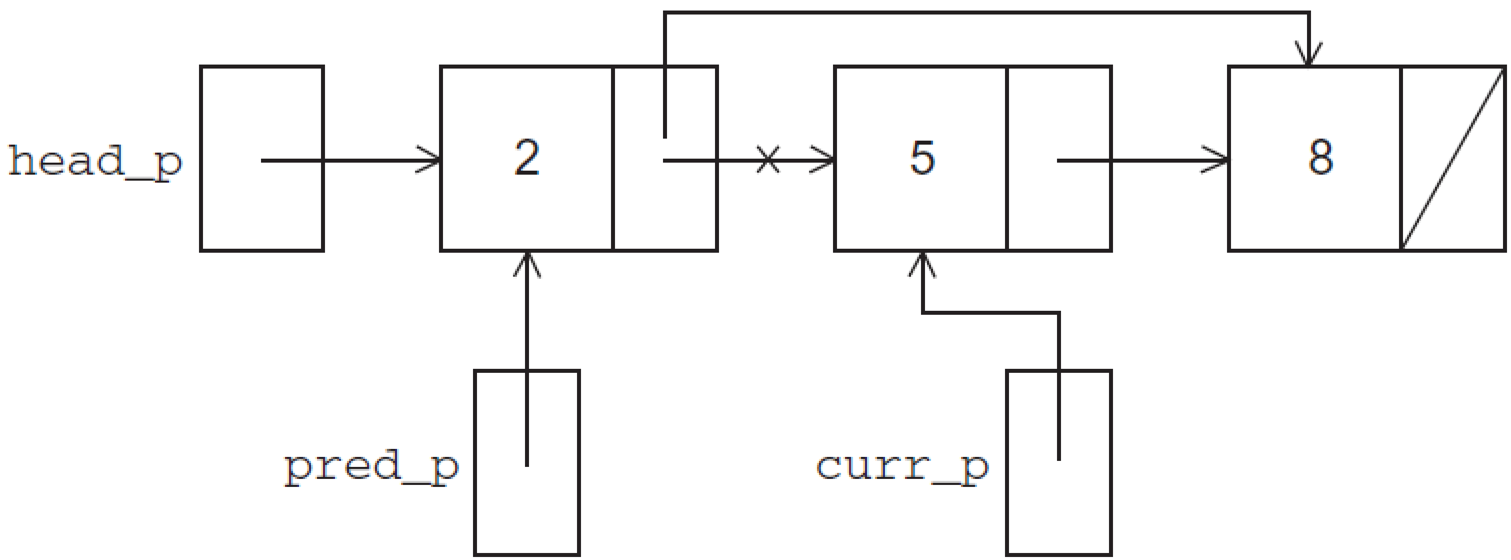
Inserting a new node into a list



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



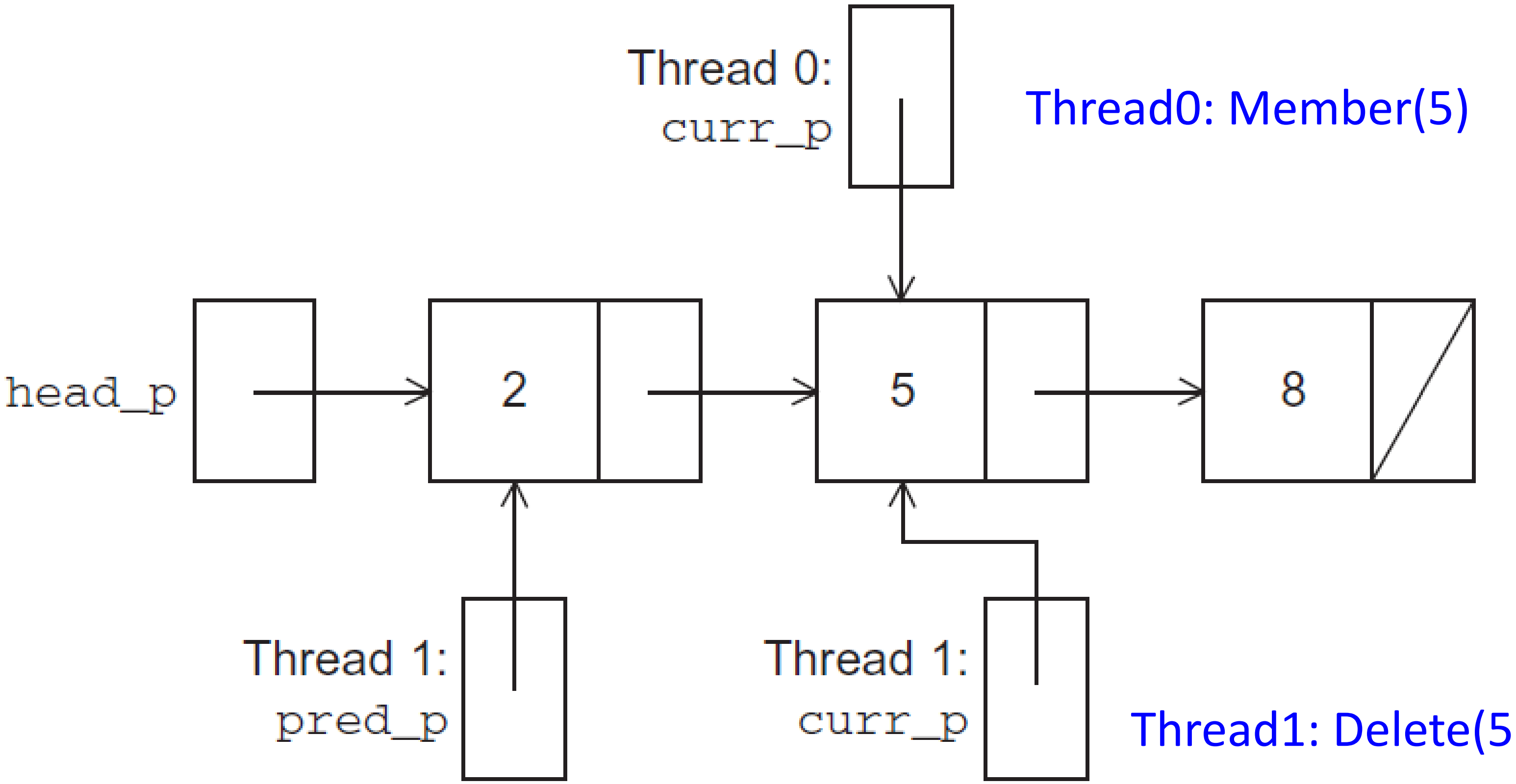
Deleting a node from a linked list

```
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

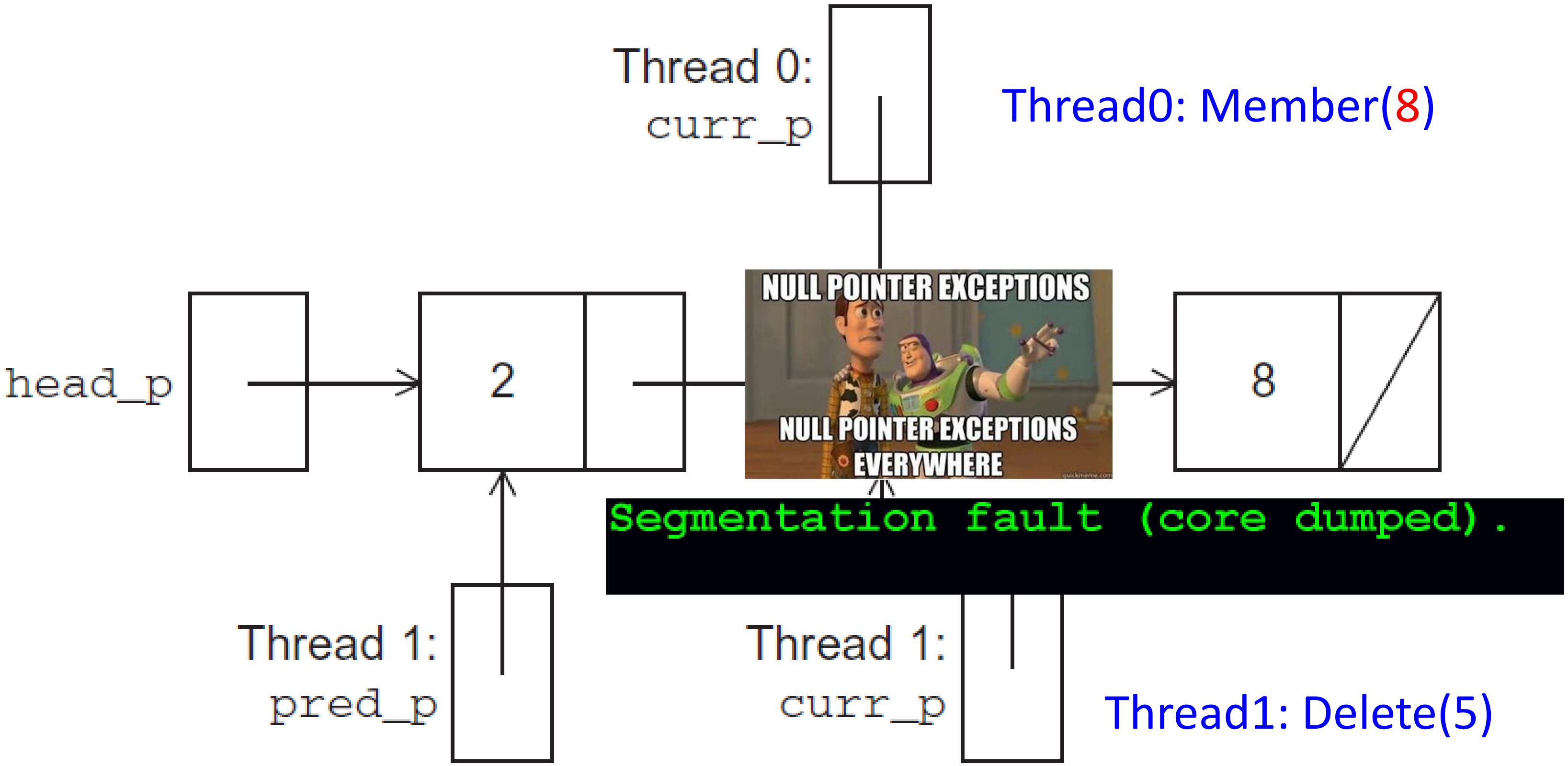
- Let's try to use these functions in a Pthreads program.
- In order to share access to the list, we can define head_p to be a global variable.
- This will simplify the function headers for Member, Insert, and Delete
    - since we won't need to pass in either head_p or a pointer to head_p
    - we'll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

Simultaneous access by two threads



Problem: Element 5 may be deleted even before thread 0 returns.

Simultaneous access by two threads



Problem: thread1 may free the memory used for the node storing 5 before thread0 can advance to the node storing 8.

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

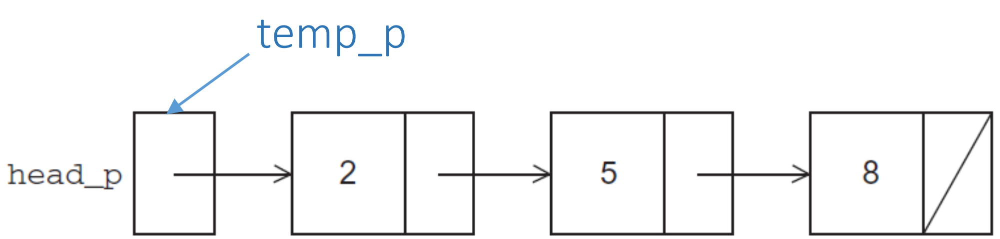
- Instead of locking the entire list, we could try to lock individual nodes.

- A "finer-grained" approach.

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

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 */
```

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.

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

If there is very few Inserts/Deletes, the RW locks do a very good job of allowing concurrent access to the list.

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

If there are a relatively large # of Inserts/Deletes, there is very little difference between RW lock and single mutex.

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.

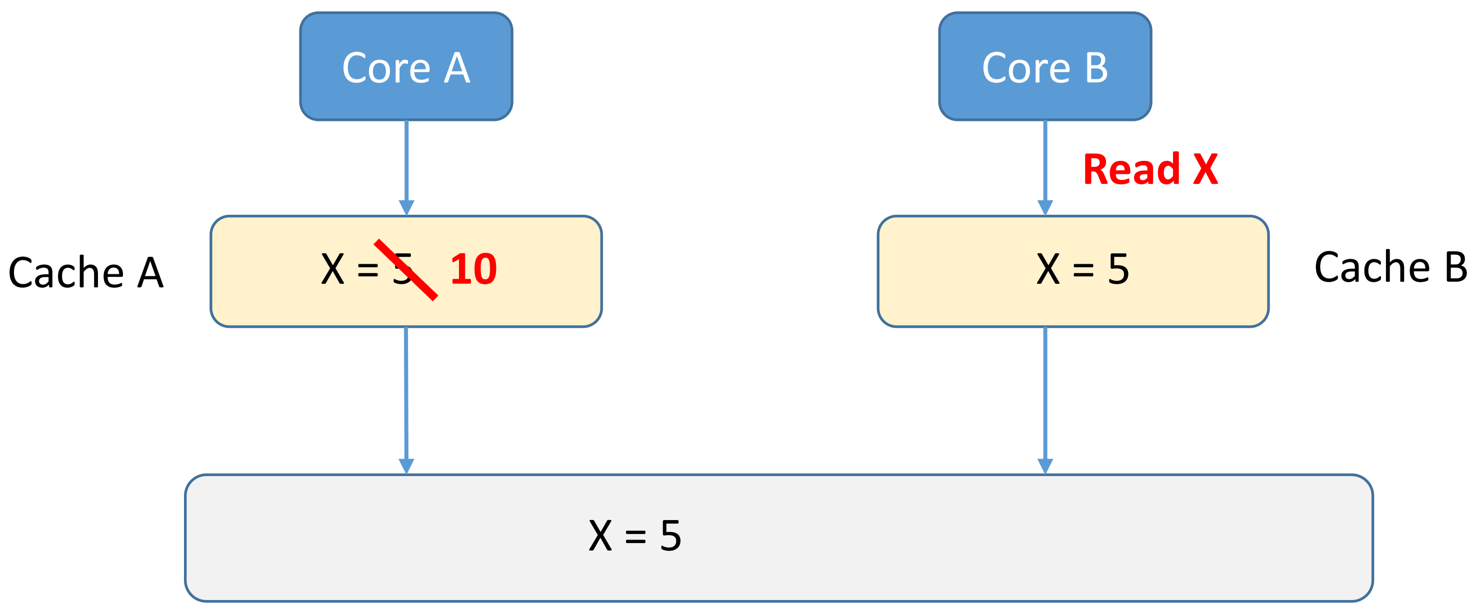
- A write-miss occurs when a core tries to update a variable that's not in cache, and it has to access main memory.

Cache coherence（缓存一致性）

- **Cache coherence（缓存一致性）问题是在多处理器系统中出现的一个问题**
  - 当多个核心同时访问同一数据时，就会产生缓存一致性问题。
- **缓存一致性问题的本质是由于每个核心的缓存是独立的**
  - 如果一个核心修改了某些数据，并将其写入其自己的缓存行，那么其他核心的缓存行可能仍然包含旧的数据。
  - 如果这些其他核心继续基于这个旧数据执行操作，就会导致错误的结果。

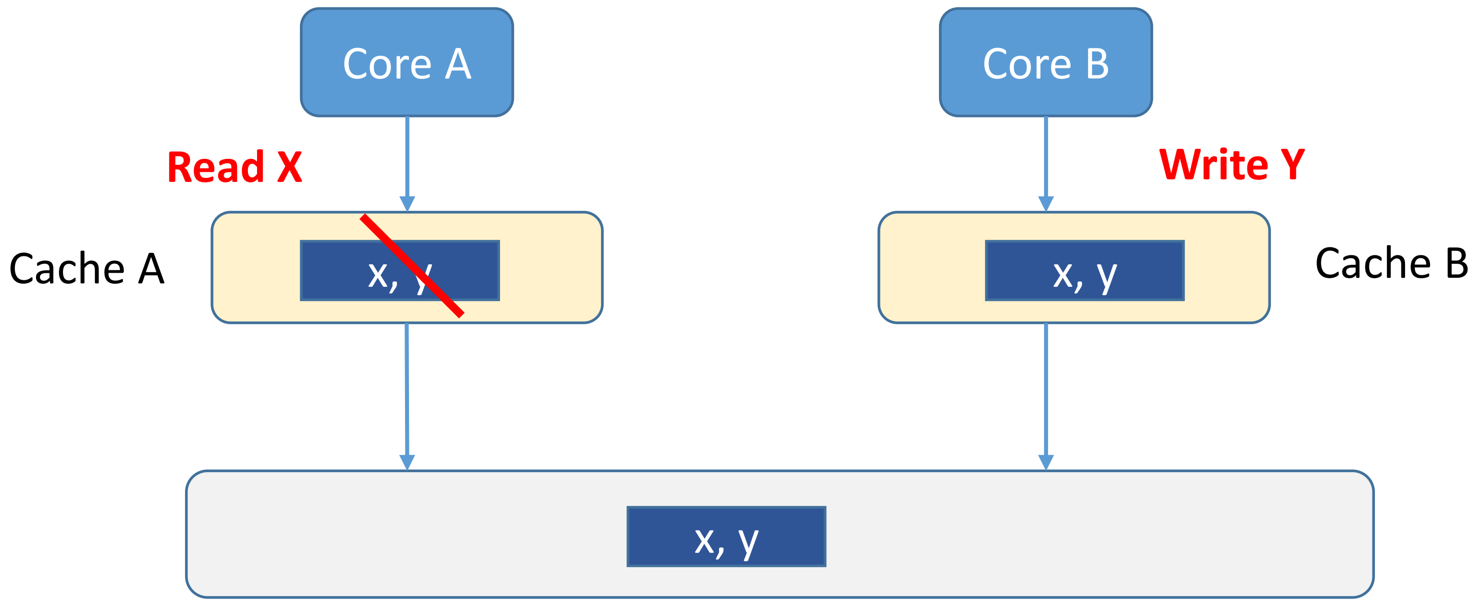
Cache coherence 例子

- 假设有一个多核处理器的系统，其中有两个核心，A和B，它们共享一个内存块。这个内存块包含一个变量 x。



False Sharing （伪共享）

- **False-sharing是一种在多核处理器系统中出现的性能问题**
  - 它发生在多个线程访问看似不同的变量，但实际上这些变量位于同一个缓存行时。
  - 在多核处理器中，每个核心都有自己的缓存，但是，当一个线程更新了一个变量，它可能会导致整个缓存行被刷新到主内存，这会影响到访问该缓存行中其他变量的其他线程



False Sharing Example

```java
public class FalseSharingExample {
    private final int[] array = new int[1024];

    public void thread1() {
        for (int i = 0; i < 1024; i++) {
            array[i] = i;
        }
    }

    public void thread2() {
        for (int i = 0; i < 1024; i++) {
            array[i] = array[i] + 1;
        }
    }
}
```

- 在上面的代码中，两个线程 thread1 和 thread2 都在更新同一个数组的不同元素。
- 尽管它们看似在更新不同的变量，但由于数组元素位于同一个缓存行，线程 thread2 的更新可能会导致线程 thread1 的缓存行被刷新到主内存，这会导致性能下降。

Pthreads matrix-vector multiplication

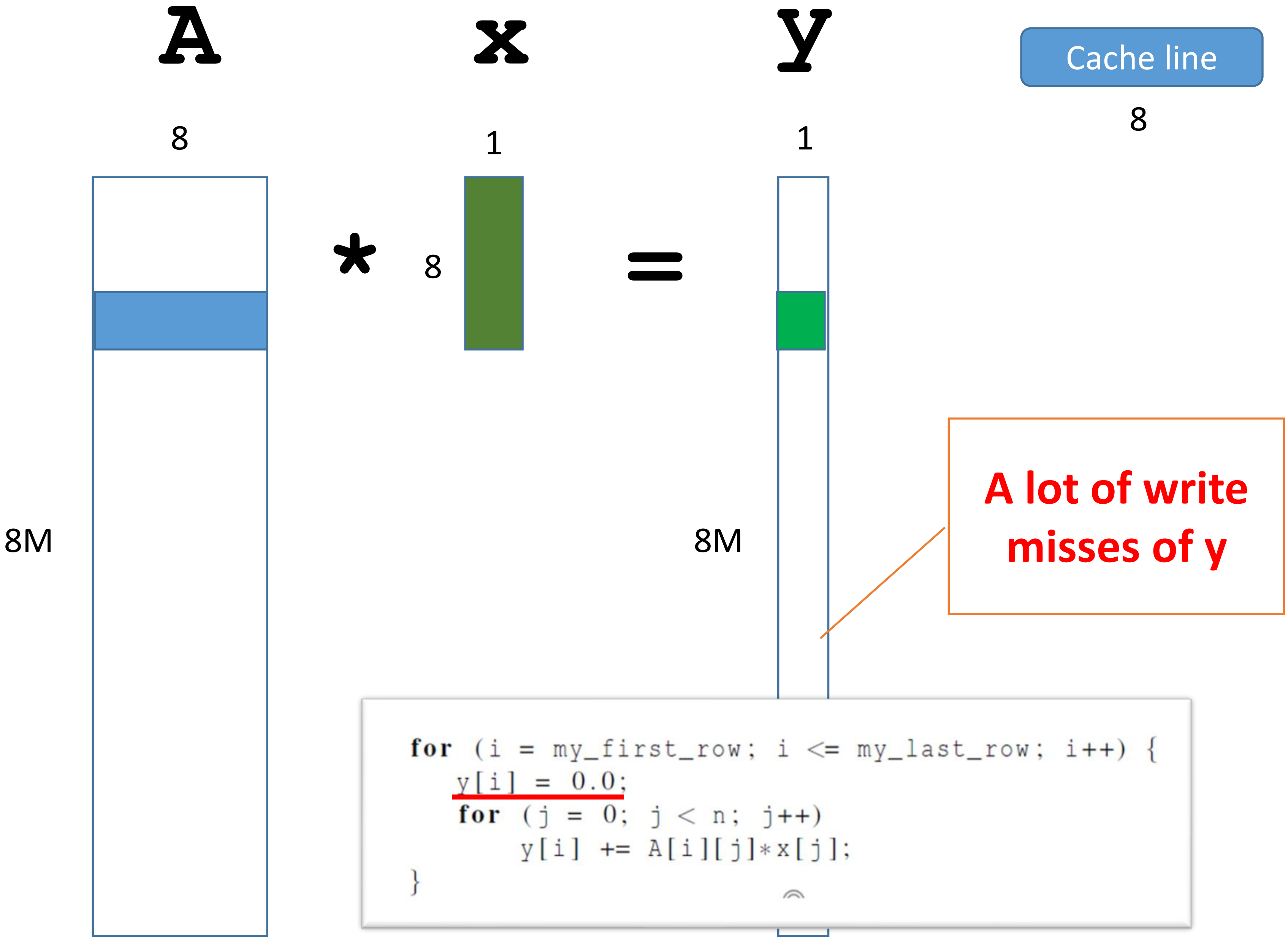
```
void *Pth_mat_vect(void* rank) {
   long my_rank = (long) rank;
   int i, j;
   int local_m = m/thread_count;
   int my_first_row = my_rank*local_m;
   int my_last_row = (my_rank+1)*local_m - 1;

   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 */
```

Q: 为什么8M*8（或8*8M）的矩阵计算时间要大于8K*8K的时间?

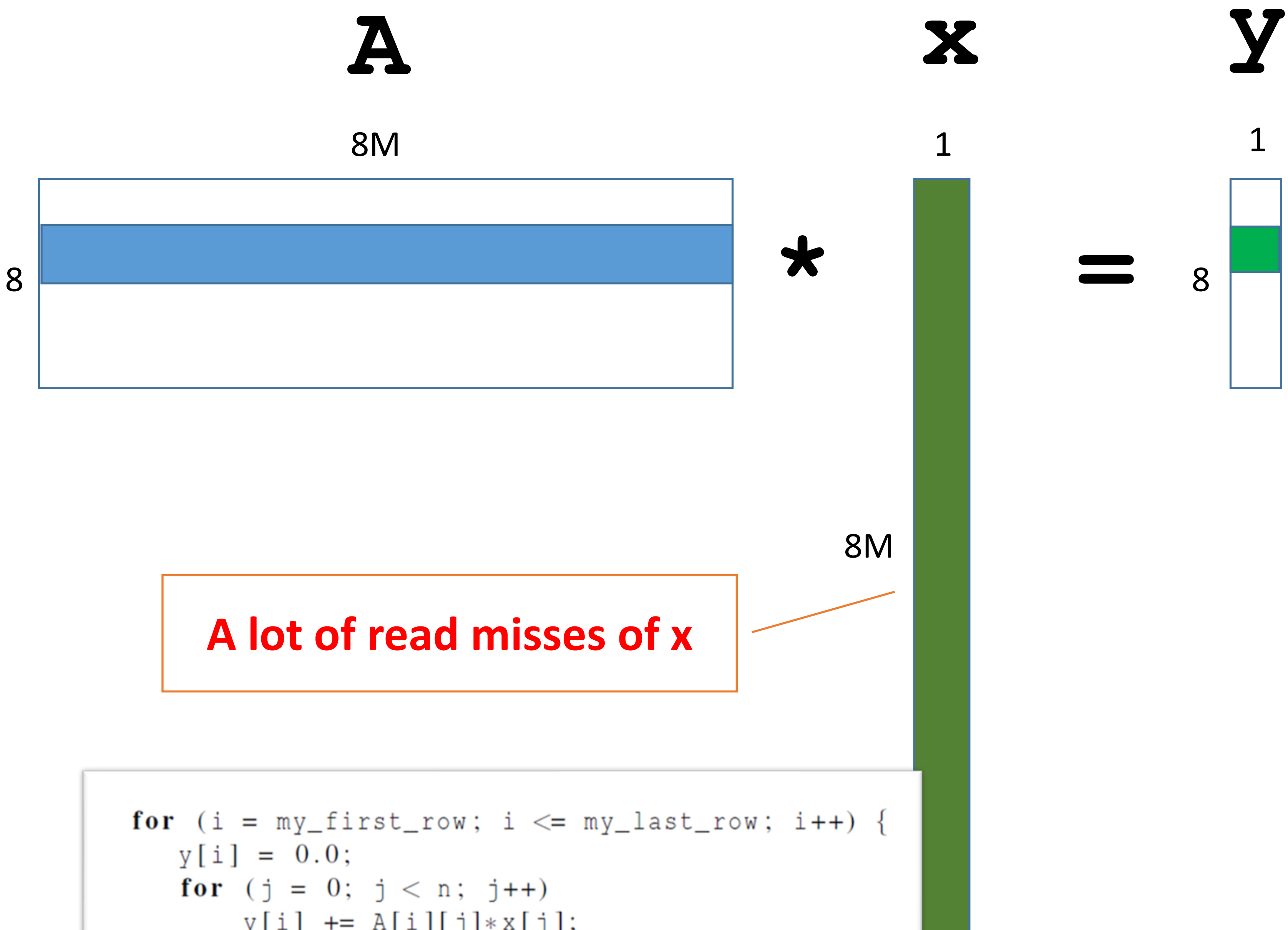
$$\mathbf{y = A*x}$$

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

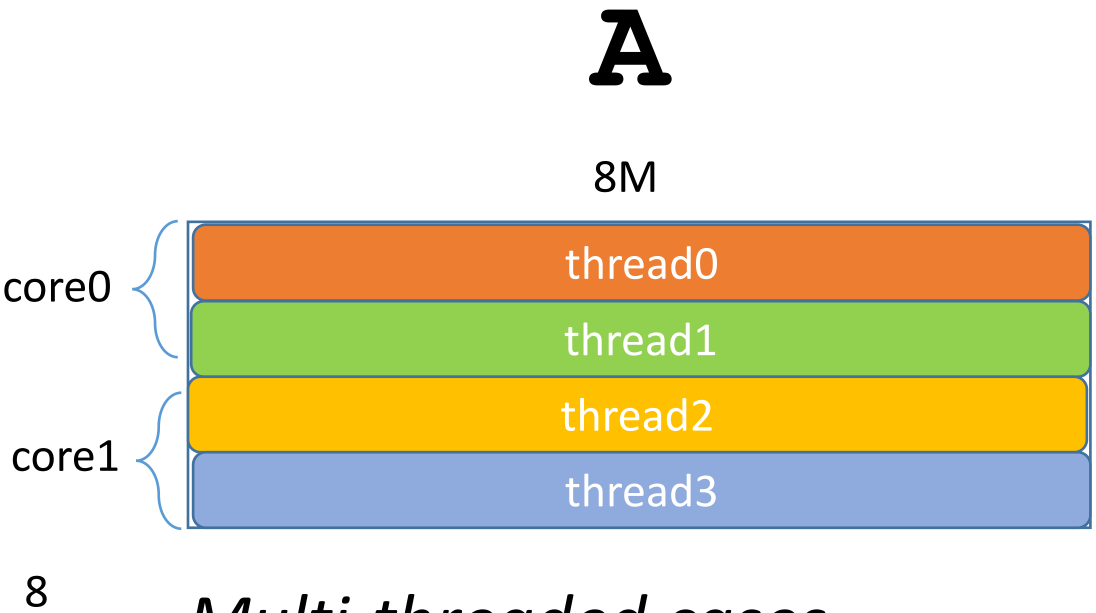
- With 1 thread, 8M*8 requires 14% more time than 8K*8K, and 8*8M requires **28% more time than** 8K*8K.
- The above differences are partially attributed to **cache performance**.
- Efficiency of multi-thread version is even **worse** for 8M*8 and 8*8M.



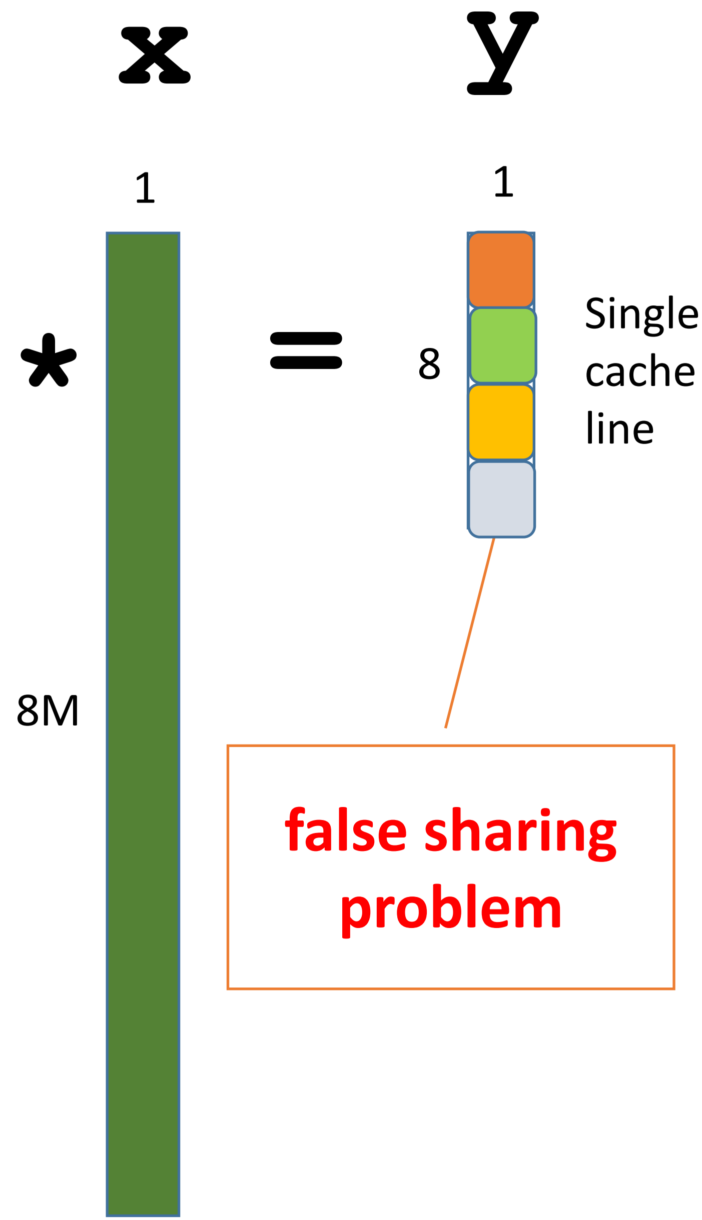

```
for (i = my_first_row; i <= my_last_row; i++) {
   y[i] = 0.0;
   for (j = 0; j < n; j++)
      y[i] += A[i][j]*x[j];
}
```




```
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];
}
```



Multi-threaded cases



Cache coherence is enforced at the "cache-line level." That is, each time any value in a cache line is written, if the line is also stored in another core's cache, the entire *line* will be invalidated

Thread-Safety

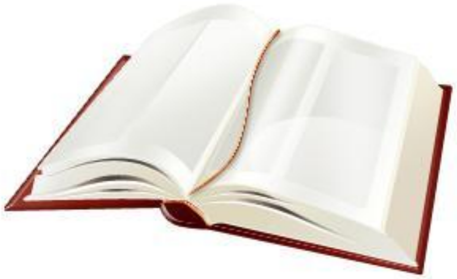
Thread-Safety

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

Example

- 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.

- Suppose we want to use multiple threads to "tokenize" a file that consists of ordinary English text.



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 t-th 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 taken from the cached copy.

```
my_string = strtok(my_line, "\t\n");
……
my_string = strtok(NULL, "\t\n");
```

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);
```

Thread 0's semaphore is initialized to 1, and others are initialized to 0

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!

Missing...

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 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 */);
```

saveptr_p keeps track of where the func is in the input string.

```
my_string = strtok(my_line,  “\t\n”);
……
my_string = strtok(NULL,  “\t\n”);
```

```
my_string = strtok_r(my_line,  “\t\n”,  &saveptr);
……
my_string = strtok_r(NULL,  “\t\n”,  &saveptr);
```

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, the accesses can result in an error, and 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.

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 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.