Programming Shared Address Space Platforms

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Topic Overview

- Thread Basics
- The POSIX Thread API
- Synchronization Primitives in Pthreads
- Controlling Thread and Synchronization Attributes
- Composite Synchronization Constructs
- OpenMP: a Standard for Directive Based Parallel Programming

Overview of Programming Models

- Programming models provide support for expressing concurrency and synchronization.
- Process based models assume that all data associated with a process is private, by default, unless otherwise specified.
- Lightweight processes and threads assume that all memory is global.
- Directive based programming models extend the threaded model by facilitating creation and synchronization of threads.

Overview of Programming Models

- A *thread* is a single stream of control in the flow of a program. A program like:

  ```
  for (row = 0; row < n; row++)
      for (column = 0; column < n; column++)
          c[row][column] =
              dot_product(get_row(a, row),
                          get_col(b, col));
  ```

  can be transformed to:

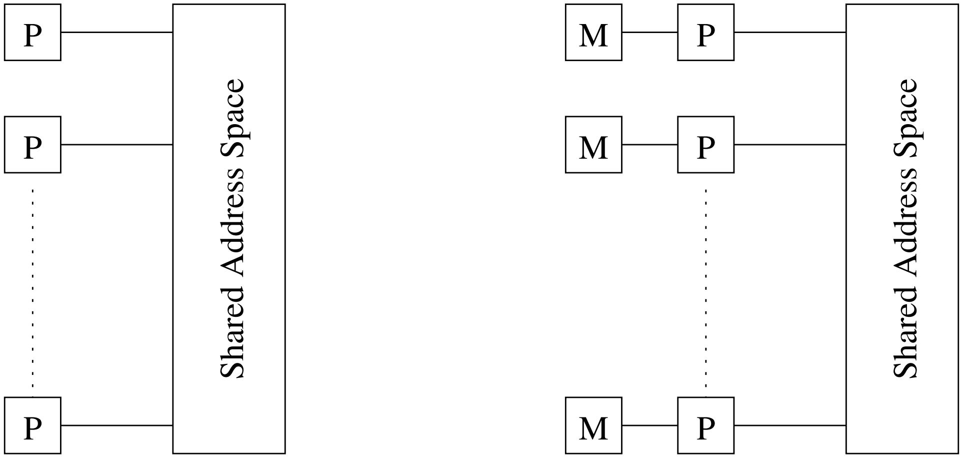
  ```
  for (row = 0; row < n; row++)
      for (column = 0; column < n; column++)
          c[row][column] =
              create_thread(
                  dot_product(get_row(a, row),
                              get_col(b, col)));
  ```

  In this case, one may think of the thread as an instance of a function that returns before the function has finished executing.

Thread Basics

- All memory in the logical machine model of a thread is globally accessible to every thread.
- The stack corresponding to the function call is generally treated as being local to the thread for liveness reasons.
- This implies a logical machine model with both global memory (default) and local memory (stacks).
- It is important to note that such a flat model may result in very poor performance since memory is physically distributed in typical machines.

Thread Basics



The logical machine model of a thread-based programming paradigm.

Thread Basics

- Threads provide software portability.
- Inherent support for latency hiding.
- Scheduling and load balancing.
- Ease of programming and widespread use.

The POSIX Thread API

- Commonly referred to as Pthreads, POSIX has emerged as the standard threads API, supported by most vendors.
- The concepts discussed here are largely independent of the API and can be used for programming with other thread APIs (NT threads, Solaris threads, Java threads, etc.) as well.

Thread Basics: Creation and Termination

- Pthreads provides two basic functions for specifying concurrency in a program:

```
#include <pthread.h>
int pthread_create (
    pthread_t   *thread_handle,
    const pthread_attr_t   *attribute,
    void *   (*thread_function)(void *),
    void   *arg);

int pthread_join (
    pthread_t   thread,
    void   **ptr);
```

- The function `pthread_create` invokes function `thread_function` as a thread.

Thread Basics: Creation and Termination (Example)

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

#define MAX_THREADS     512
void *compute_pi (void *);
....

main() {
    ...
    pthread_t p_threads[MAX_THREADS];
    pthread_attr_t  attr;

    pthread_attr_init (&attr);
    for (i=0; i< num_threads; i++) {
        hits[i] = i;
        pthread_create(&p_threads[i], &attr, compute_pi,
            (void *) &hits[i]);
    }
    for (i=0; i< num_threads; i++) {
        pthread_join(p_threads[i], NULL);
        total_hits += hits[i];
    }
    ...
}
```

Thread Basics: Creation and Termination (Example)

```
void *compute_pi (void *s) {
    int seed, i, *hit_pointer;
    double rand_no_x, rand_no_y;
    int local_hits;

    hit_pointer = (int *) s;
    seed = *hit_pointer;
    local_hits = 0;
    for (i = 0; i < sample_points_per_thread; i++) {
        rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
        rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
        if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
            (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
            local_hits ++;
        seed *= i;
    }
    *hit_pointer = local_hits;
    pthread_exit(0);
}
```

Programming and Performance Notes

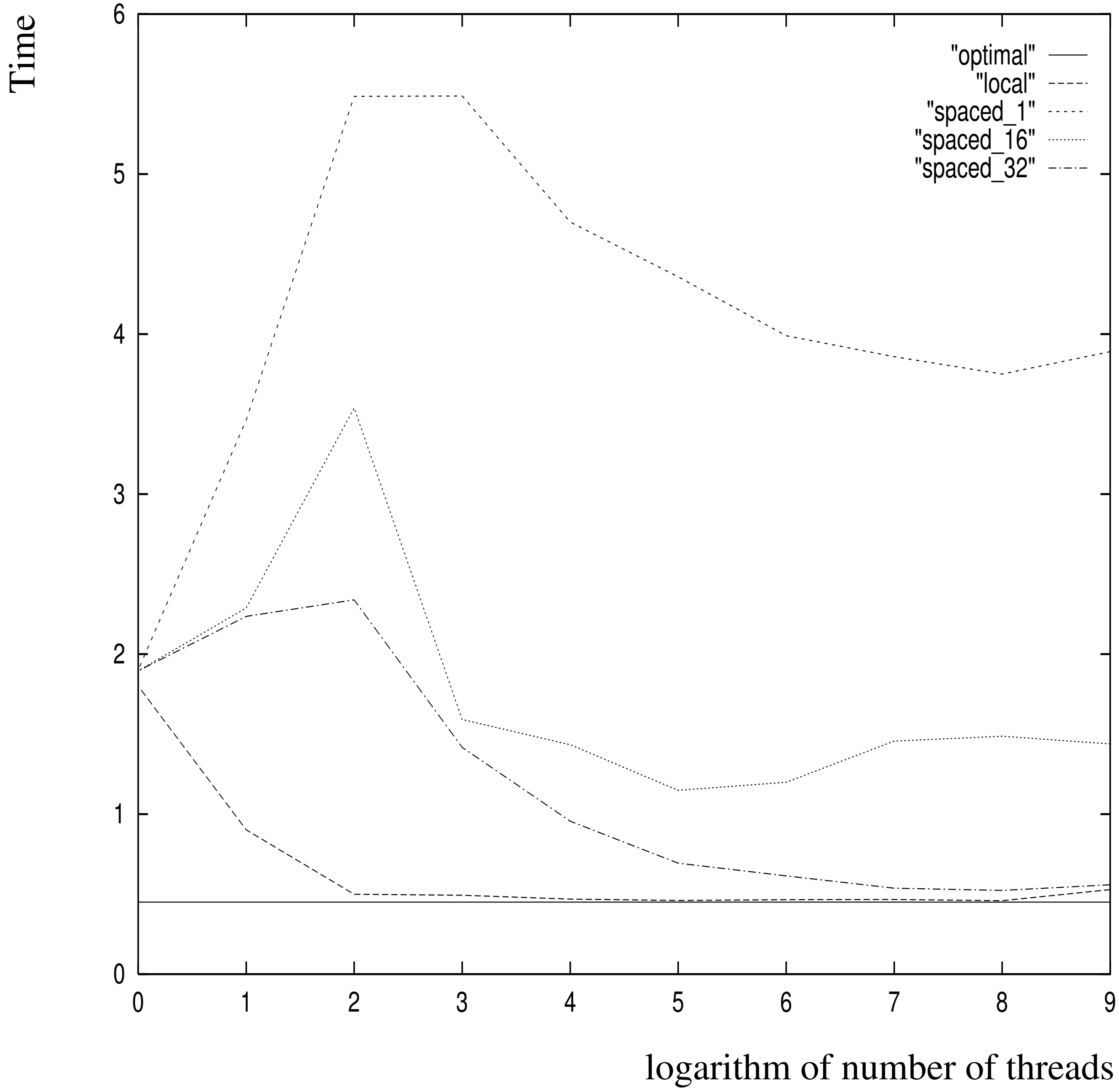
- Note the use of the function `rand_r` (instead of superior random number generators such as `drand48`).

- Executing this on a 4-processor SGI Origin, we observe a 3.91 fold speedup at 32 threads. This corresponds to a parallel efficiency of 0.98!

- We can also modify the program slightly to observe the effect of false-sharing.

- The program can also be used to assess the secondary cache line size.

Programming and Performance Notes



Execution time of the `compute_pi` program.

Synchronization Primitives in Pthreads

- When multiple threads attempt to manipulate the same data item, the results can often be incoherent if proper care is not taken to synchronize them.
- Consider:

```
/* each thread tries to update variable best_cost as follows */
if (my_cost < best_cost)
    best_cost = my_cost;
```

- Assume that there are two threads, the initial value of `best_cost` is 100, and the values of `my_cost` are 50 and 75 at threads t1 and t2.
- Depending on the schedule of the threads, the value of `best_cost` could be 50 or 75!
- The value 75 does not correspond to any serialization of the threads.

Mutual Exclusion

- The code in the previous example corresponds to a critical segment; i.e., a segment that must be executed by only one thread at any time.
- Critical segments in Pthreads are implemented using mutex locks.
- Mutex-locks have two states: locked and unlocked. At any point of time, only one thread can lock a mutex lock. A lock is an atomic operation.
- A thread entering a critical segment first tries to get a lock. It goes ahead when the lock is granted.

Mutual Exclusion

The Pthreads API provides the following functions for handling mutex-locks:

```
int pthread_mutex_lock (
    pthread_mutex_t   *mutex_lock);

int pthread_mutex_unlock (
    pthread_mutex_t *mutex_lock);

int pthread_mutex_init (
    pthread_mutex_t   *mutex_lock,
    const pthread_mutexattr_t   *lock_attr);
```

Mutual Exclusion

We can now write our previously incorrect code segment as:

```
pthread_mutex_t minimum_value_lock;
...
main() {
    ....
    pthread_mutex_init(&minimum_value_lock, NULL);
    ....
}

void *find_min(void *list_ptr) {
    ....
    pthread_mutex_lock(&minimum_value_lock);
    if (my_min < minimum_value)
        minimum_value = my_min;
    /* and unlock the mutex */
    pthread_mutex_unlock(&minimum_value_lock);
}
```

Producer-Consumer Using Locks

The producer-consumer scenario imposes the following constraints:

- The producer thread must not overwrite the shared buffer when the previous task has not been picked up by a consumer thread.
- The consumer threads must not pick up tasks until there is something present in the shared data structure.
- Individual consumer threads should pick up tasks one at a time.

Producer-Consumer Using Locks

```
pthread_mutex_t task_queue_lock;
int task_available;
...
main() {
     ....
     task_available = 0;
     pthread_mutex_init(&task_queue_lock, NULL);
     ....
}

void *producer(void *producer_thread_data) {
     ....
     while (!done()) {
          inserted = 0;
          create_task(&my_task);
          while (inserted == 0) {
               pthread_mutex_lock(&task_queue_lock);
               if (task_available == 0) {
                    insert_into_queue(my_task);
                    task_available = 1;
                    inserted = 1;
               }
               pthread_mutex_unlock(&task_queue_lock);
          }
     }
}
```

Producer-Consumer Using Locks

```
void *consumer(void *consumer_thread_data) {
    int extracted;
    struct task my_task;
    /* local data structure declarations */
    while (!done()) {
        extracted = 0;
        while (extracted == 0) {
            pthread_mutex_lock(&task_queue_lock);
            if (task_available == 1) {
                extract_from_queue(&my_task);
                task_available = 0;
                extracted = 1;
            }
            pthread_mutex_unlock(&task_queue_lock);
        }
        process_task(my_task);
    }
}
```

Types of Mutexes

- Pthreads supports three types of mutexes – normal, recursive, and error-check.
- A normal mutex deadlocks if a thread that already has a lock tries a second lock on it.
- A recursive mutex allows a single thread to lock a mutex as many times as it wants. It simply increments a count on the number of locks. A lock is relinquished by a thread when the count becomes zero.
- An error check mutex reports an error when a thread with a lock tries to lock it again (as opposed to deadlocking in the first case, or granting the lock, as in the second case).
- The type of the mutex can be set in the attributes object before it is passed at time of initialization.

Overheads of Locking

- Locks represent serialization points since critical sections must be executed by threads one after the other.

- Encapsulating large segments of the program within locks can lead to significant performance degradation.

- It is often possible to reduce the idling overhead associated with locks using an alternate function, `pthread_mutex_trylock`.

```
int pthread_mutex_trylock (
    pthread_mutex_t *mutex_lock);
```

- `pthread_mutex_trylock` is typically much faster than `pthread_mutex` on typical systems since it does not have to deal with queues associated with locks for multiple threads waiting on the lock.

Alleviating Locking Overhead (Example)

```
/* Finding k matches in a list */
void *find_entries(void *start_pointer) {
    /* This is the thread function */
    struct database_record *next_record;
    int count;
    current_pointer = start_pointer;
    do {
        next_record = find_next_entry(current_pointer);
        count = output_record(next_record);
    } while (count < requested_number_of_records);
}

int output_record(struct database_record *record_ptr) {
    int count;
    pthread_mutex_lock(&output_count_lock);
    output_count ++;
    count = output_count;
    pthread_mutex_unlock(&output_count_lock);
    if (count <= requested_number_of_records)
        print_record(record_ptr);
    return (count);
}
```

Alleviating Locking Overhead (Example)

```
/* rewritten output_record function */

int output_record(struct database_record *record_ptr) {
    int count;
    int lock_status;
    lock_status = pthread_mutex_trylock(&output_count_lock);
    if (lock_status == EBUSY) {
        insert_into_local_list(record_ptr);
        return(0);
    }
    else {
        count = output_count;
        output_count += number_on_local_list + 1;
        pthread_mutex_unlock(&output_count_lock);
        print_records(record_ptr, local_list,
              requested_number_of_records - count);
        return(count + number_on_local_list + 1);
    }
}
```

Condition Variables for Synchronization

- A condition variable allows a thread to block itself until specified data reaches a predefined state.
- A condition variable is associated with this predicate. When the predicate becomes true, the condition variable is used to signal one or more threads waiting on the condition.
- A single condition variable may be associated with more than one predicate.
- A condition variable always has a mutex associated with it. A thread locks this mutex and tests the predicate defined on the shared variable.
- If the predicate is not true, the thread waits on the condition variable associated with the predicate using the function `pthread_cond_wait`.

Condition Variables for Synchronization

Pthreads provides the following functions for condition variables:

```
int pthread_cond_wait(pthread_cond_t *cond,
    pthread_mutex_t *mutex);

int pthread_cond_signal(pthread_cond_t *cond);

int pthread_cond_broadcast(pthread_cond_t *cond);

int pthread_cond_init(pthread_cond_t *cond,
    const pthread_condattr_t *attr);

int pthread_cond_destroy(pthread_cond_t *cond);
```

Producer-Consumer Using Condition Variables

```
pthread_cond_t cond_queue_empty, cond_queue_full;
pthread_mutex_t task_queue_cond_lock;
int task_available;

/* other data structures here */

main() {
    /* declarations and initializations */
    task_available = 0;
    pthread_init();
    pthread_cond_init(&cond_queue_empty, NULL);
    pthread_cond_init(&cond_queue_full, NULL);
    pthread_mutex_init(&task_queue_cond_lock, NULL);
    /* create and join producer and consumer threads */
}
```

Producer-Consumer Using Condition Variables

```
void *producer(void *producer_thread_data) {
    int inserted;
    while (!done()) {
        create_task();
        pthread_mutex_lock(&task_queue_cond_lock);
        while (task_available == 1)
            pthread_cond_wait(&cond_queue_empty,
                &task_queue_cond_lock);
        insert_into_queue();
        task_available = 1;
        pthread_cond_signal(&cond_queue_full);
        pthread_mutex_unlock(&task_queue_cond_lock);
    }
}
```

Producer-Consumer Using Condition Variables

```
void *consumer(void *consumer_thread_data) {
    while (!done()) {
        pthread_mutex_lock(&task_queue_cond_lock);
        while (task_available == 0)
            pthread_cond_wait(&cond_queue_full,
                &task_queue_cond_lock);
        my_task = extract_from_queue();
        task_available = 0;
        pthread_cond_signal(&cond_queue_empty);
        pthread_mutex_unlock(&task_queue_cond_lock);
        process_task(my_task);
    }
}
```

Controlling Thread and Synchronization Attributes

- The Pthreads API allows a programmer to change the default attributes of entities using *attributes objects*.
- An attributes object is a data-structure that describes entity (thread, mutex, condition variable) properties.
- Once these properties are set, the attributes object can be passed to the method initializing the entity.
- Enhances modularity, readability, and ease of modification.

Attributes Objects for Threads

- Use `pthread_attr_init` to create an attributes object.
- Individual properties associated with the attributes object can be changed using the following functions:
  `pthread_attr_setdetachstate`,
  `pthread_attr_setguardsize_np`,
  `pthread_attr_setstacksize`,
  `pthread_attr_setinheritsched`,
  `pthread_attr_setschedpolicy`, and
  `pthread_attr_setschedparam`.

Attributes Objects for Mutexes

- Initialize the attrributes object using function: `pthread_mutexattr_init`.
- The function `pthread_mutexattr_settype_np` can be used for setting the type of mutex specified by the mutex attributes object.

```
pthread_mutexattr_settype_np (
    pthread_mutexattr_t   *attr,
    int    type);
```

Here, `type` specifies the type of the mutex and can take one of:

- `PTHREAD_MUTEX_NORMAL_NP`
- `PTHREAD_MUTEX_RECURSIVE_NP`
- `PTHREAD_MUTEX_ERRORCHECK_NP`

Composite Synchronization Constructs

- By design, Pthreads provide support for a basic set of operations.

- Higher level constructs can be built using basic synchronization constructs.

- We discuss two such constructs – read-write locks and barriers.

Read-Write Locks

- In many applications, a data structure is read frequently but written infrequently. For such applications, we should use read-write locks.
- A read lock is granted when there are other threads that may already have read locks.
- If there is a write lock on the data (or if there are queued write locks), the thread performs a condition wait.
- If there are multiple threads requesting a write lock, they must perform a condition wait.
- With this description, we can design functions for read locks `mylib_rwlock_rlock`, write locks `mylib_rwlock_wlock`, and unlocking `mylib_rwlock_unlock`.

Read-Write Locks

- The lock data type `mylib_rwlock_t` holds the following:
  - a count of the number of readers,
  - the writer (a 0/1 integer specifying whether a writer is present),
  - a condition variable `readers_proceed` that is signaled when readers can proceed,
  - a condition variable `writer_proceed` that is signaled when one of the writers can proceed,
  - a count `pending_writers` of pending writers, and
  - a mutex `read_write_lock` associated with the shared data structure.

Read-Write Locks

```
typedef struct {
    int readers;
    int writer;
    pthread_cond_t readers_proceed;
    pthread_cond_t writer_proceed;
    int pending_writers;
    pthread_mutex_t read_write_lock;
} mylib_rwlock_t;


void mylib_rwlock_init (mylib_rwlock_t *l) {
   l -> readers = l -> writer = l -> pending_writers = 0;
   pthread_mutex_init(&(l -> read_write_lock), NULL);
   pthread_cond_init(&(l -> readers_proceed), NULL);
   pthread_cond_init(&(l -> writer_proceed), NULL);
}
```

Read-Write Locks

```
void mylib_rwlock_rlock(mylib_rwlock_t *l) {
   /* if there is a write lock or pending writers, perform condition
   wait.. else increment count of readers and grant read lock */

   pthread_mutex_lock(&(l -> read_write_lock));
   while ((l -> pending_writers > 0) || (l -> writer > 0))
       pthread_cond_wait(&(l -> readers_proceed),
          &(l -> read_write_lock));
   l -> readers ++;
   pthread_mutex_unlock(&(l -> read_write_lock));
}
```

Read-Write Locks

```
void mylib_rwlock_wlock(mylib_rwlock_t *l) {
   /* if there are readers or writers, increment pending writers
   count and wait. On being woken, decrement pending writers
   count and increment writer count */

   pthread_mutex_lock(&(l -> read_write_lock));
   while ((l -> writer > 0) || (l -> readers > 0))  {
       l -> pending_writers ++;
       pthread_cond_wait(&(l -> writer_proceed),
          &(l -> read_write_lock));
   }
   l -> pending_writers --;
   l -> writer ++
   pthread_mutex_unlock(&(l -> read_write_lock));
}
```

Read-Write Locks

```
void mylib_rwlock_unlock(mylib_rwlock_t *l) {
   /* if there is a write lock then unlock, else if there are
   read locks, decrement count of read locks. If the count
   is 0 and there is a pending writer, let it through, else
   if there are pending readers, let them all go through */

   pthread_mutex_lock(&(l -> read_write_lock));
   if (l -> writer > 0)
      l -> writer = 0;
   else if (l -> readers > 0)
      l -> readers --;
   pthread_mutex_unlock(&(l -> read_write_lock));
   if ((l -> readers == 0) && (l -> pending_writers > 0))
      pthread_cond_signal(&(l -> writer_proceed));
   else if (l -> readers > 0)
      pthread_cond_broadcast(&(l -> readers_proceed));
}
```

Barriers

- As in MPI, a barrier holds a thread until all threads participating in the barrier have reached it.
- Barriers can be implemented using a counter, a mutex and a condition variable.
- A single integer is used to keep track of the number of threads that have reached the barrier.
- If the count is less than the total number of threads, the threads execute a condition wait.
- The last thread entering (and setting the count to the number of threads) wakes up all the threads using a condition broadcast.

Barriers

```
typedef struct {
    pthread_mutex_t count_lock;
    pthread_cond_t ok_to_proceed;
    int count;
} mylib_barrier_t;

void mylib_init_barrier(mylib_barrier_t *b) {
    b -> count = 0;
    pthread_mutex_init(&(b -> count_lock), NULL);
    pthread_cond_init(&(b -> ok_to_proceed), NULL);
}
```

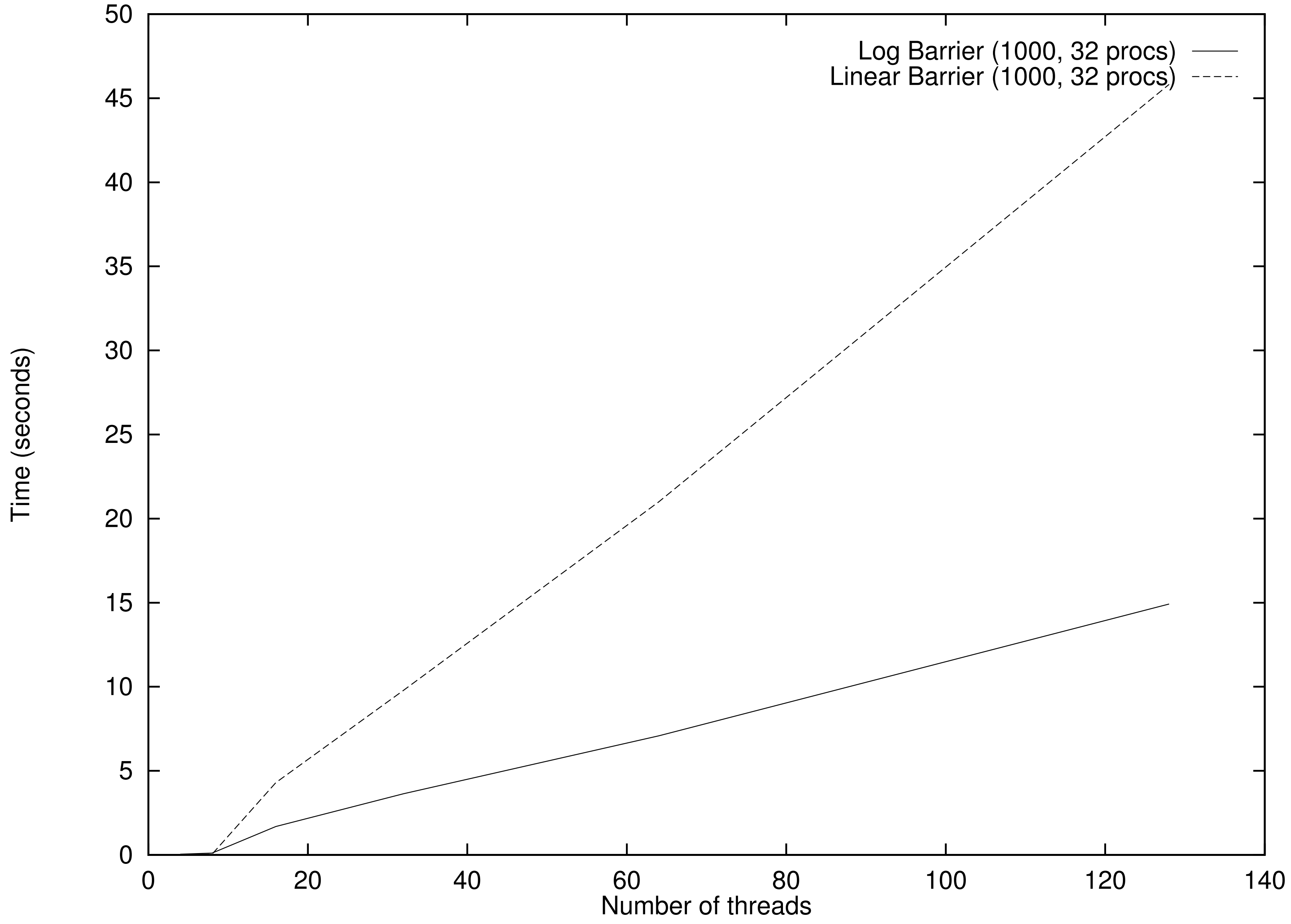
Barriers

```
void mylib_barrier (mylib_barrier_t *b, int num_threads) {
    pthread_mutex_lock(&(b -> count_lock));
    b -> count ++;
    if (b -> count == num_threads) {
        b -> count = 0;
        pthread_cond_broadcast(&(b -> ok_to_proceed));
    }
    else
        while (pthread_cond_wait(&(b -> ok_to_proceed),
            &(b -> count_lock)) != 0);
    pthread_mutex_unlock(&(b -> count_lock));
}
```

Barriers

- The barrier described above is called a linear barrier.
- The trivial lower bound on execution time of this function is therefore $O(n)$ for n threads.
- This implementation of a barrier can be speeded up using multiple barrier variables organized in a tree.
- We use $n/2$ condition variable-mutex pairs for implementing a barrier for n threads.
- At the lowest level, threads are paired up and each pair of threads shares a single condition variable-mutex pair.
- Once both threads arrive, one of the two moves on, the other one waits.
- This process repeats up the tree.
- This is also called a log barrier and its runtime grows as $O(\log p)$.

Barrier



Execution time of 1000 sequential and logarithmic barriers as a function of number of threads on a 32 processor SGI Origin 2000.

Tips for Designing Asynchronous Programs

- Never rely on scheduling assumptions when exchanging data.
- Never rely on liveness of data resulting from assumptions on scheduling.
- Do not rely on scheduling as a means of synchronization.
- Where possible, define and use group synchronizations and data replication.

OpenMP: a Standard for Directive Based Parallel Programming

- OpenMP is a directive-based API that can be used with FORTRAN, C, and C++ for programming shared address space machines.

- OpenMP directives provide support for concurrency, synchronization, and data handling while obviating the need for explicitly setting up mutexes, condition variables, data scope, and initialization.

OpenMP Programming Model

- OpenMP directives in C and C++ are based on the `#pragma` compiler directives.

- A directive consists of a directive name followed by clauses.

```
#pragma omp directive [clause list]
```

- OpenMP programs execute serially until they encounter the `parallel` directive, which creates a group of threads.

```
#pragma omp parallel [clause list]
/* structured block */
```

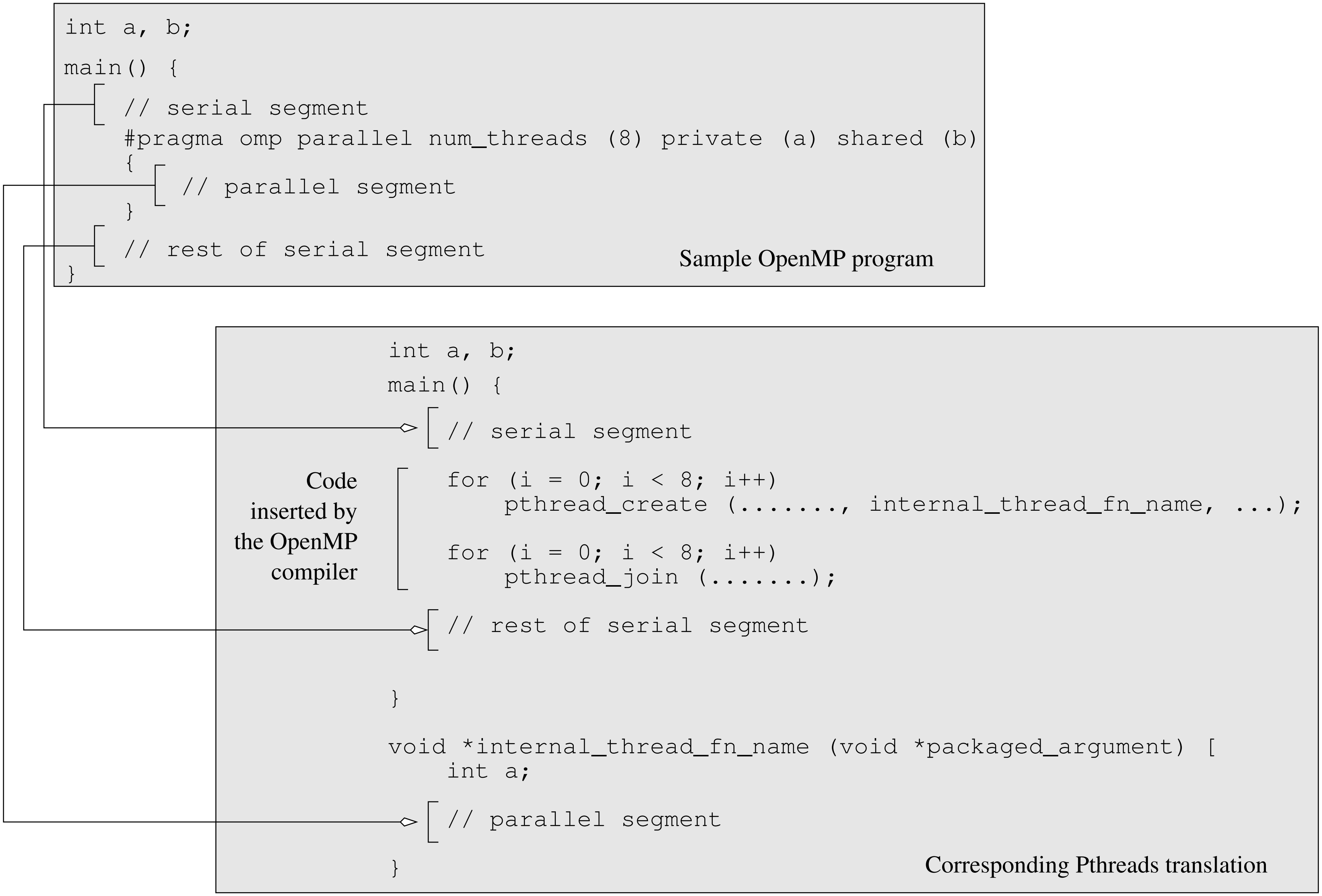
- The main thread that encounters the `parallel` directive becomes the *master* of this group of threads and is assigned the thread id 0 within the group.

OpenMP Programming Model

The clause list is used to specify conditional parallelization, number of threads, and data handling.

- **Conditional Parallelization:** The clause `if (scalar expression)` determines whether the parallel construct results in creation of threads.
- **Degree of Concurrency:** The clause `num_threads (integer expression)` specifies the number of threads that are created.
- **Data Handling:** The clause `private (variable list)` indicates variables local to each thread. The clause `firstprivate (variable list)` is similar to the `private`, except values of variables are initialized to corresponding values before the parallel directive. The clause `shared (variable list)` indicates that variables are shared across all the threads.

OpenMP Programming Model



```
int a, b;
main() {
    // serial segment
    #pragma omp parallel num_threads (8) private (a) shared (b)
    {
        // parallel segment
    }
    // rest of serial segment
}
```

Sample OpenMP program

```
int a, b;
main() {
    // serial segment

    for (i = 0; i < 8; i++)
        pthread_create (......., internal_thread_fn_name, ...);

    for (i = 0; i < 8; i++)
        pthread_join (.......);

    // rest of serial segment

}

void *internal_thread_fn_name (void *packaged_argument) [
    int a;
    // parallel segment
}
```

Code inserted by the OpenMP compiler

Corresponding Pthreads translation

A sample OpenMP program along with its Pthreads translation that might be performed by an OpenMP compiler.

OpenMP Programming Model

```
#pragma omp parallel if (is_parallel == 1) num_threads(8) \
                     private (a) shared (b) firstprivate(c)
{
    /* structured block */
}
```

- If the value of the variable `is_parallel` equals one, eight threads are created.
- Each of these threads gets private copies of variables `a` and `c`, and shares a single value of variable `b`.
- The value of each copy of `c` is initialized to the value of `c` before the parallel directive.
- The default state of a variable is specified by the clause `default (shared)` or `default (none)`.

Reduction Clause in OpenMP

- The `reduction` clause specifies how multiple local copies of a variable at different threads are combined into a single copy at the master when threads exit.

- The usage of the `reduction` clause is `reduction (operator: variable list)`.

- The variables in the list are implicitly specified as being private to threads.

- The `operator` can be one of `+, *, -, &, |, ^, &&,` and `||`.

```
#pragma omp parallel reduction(+: sum) num_threads(8)
{
    /* compute local sums here */
}
/* sum here contains sum of all local instances of sums */
```

OpenMP Programming: Example

```
/* ******************************************************
   An OpenMP version of a threaded program to compute PI.
   ****************************************************** */

    #pragma omp parallel default(private) shared (npoints) \
                         reduction(+: sum) num_threads(8)
    {
      num_threads = omp_get_num_threads();
      sample_points_per_thread = npoints / num_threads;
      sum = 0;
      for (i = 0; i < sample_points_per_thread; i++) {
        rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
        rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
        if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
            (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
            sum ++;
      }
    }
```

Specifying Concurrent Tasks in OpenMP

- The `parallel` directive can be used in conjunction with other directives to specify concurrency across iterations and tasks.
- OpenMP provides two directives – `for` and `sections` - to specify concurrent iterations and tasks.
- The `for` directive is used to split parallel iteration spaces across threads. The general form of a `for` directive is as follows:

```
#pragma omp for [clause list]
    /* for loop */
```

- The clauses that can be used in this context are: `private`, `firstprivate`, `lastprivate`, `reduction`, `schedule`, `nowait`, and `ordered`.

Specifying Concurrent Tasks in OpenMP: Example

```
#pragma omp parallel default(private) shared (npoints) \
                     reduction(+: sum) num_threads(8)
{
  sum = 0;
  #pragma omp for
  for (i = 0; i < npoints; i++) {
    rand_no_x =(double)(rand_r(&seed))/(double)((2<<14)-1);
    rand_no_y =(double)(rand_r(&seed))/(double)((2<<14)-1);
    if (((rand_no_x - 0.5) * (rand_no_x - 0.5) +
        (rand_no_y - 0.5) * (rand_no_y - 0.5)) < 0.25)
        sum ++;
  }
}
```

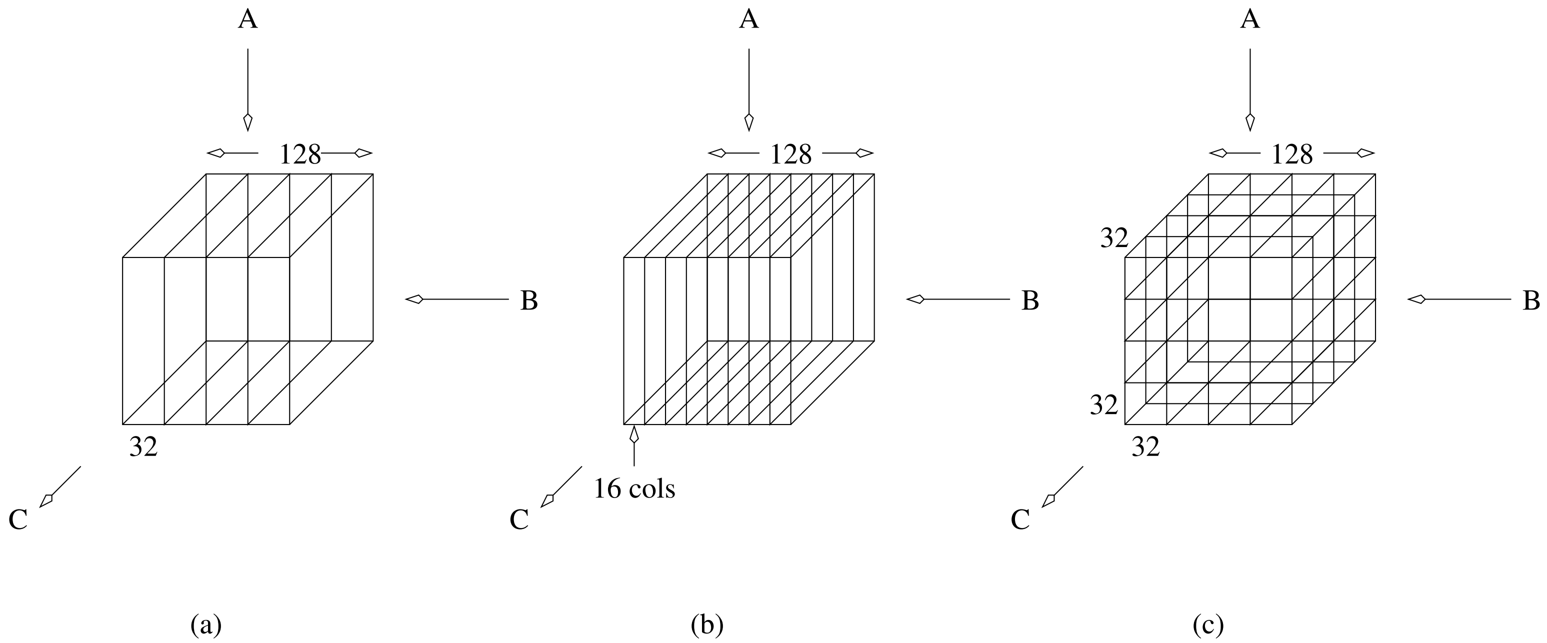
Assigning Iterations to Threads

- The `schedule` clause of the `for` directive deals with the assignment of iterations to threads.
- The general form of the `schedule` directive is `schedule(scheduling_class[, parameter]).`
- OpenMP supports four scheduling classes: `static`, `dynamic`, `guided`, and `runtime`.

Assigning Iterations to Threads: Example

```
/* static scheduling of matrix multiplication loops */
#pragma omp parallel default(private) shared (a, b, c, dim) \
                     num_threads(4)
    #pragma omp for schedule(static)
    for (i = 0; i < dim; i++) {
        for (j = 0; j < dim; j++) {
            c(i,j) = 0;
            for (k = 0; k < dim; k++) {
                c(i,j) += a(i, k) * b(k, j);
            }
        }
    }
```

Assigning Iterations to Threads: Example



Three different schedules using the static scheduling class of OpenMP.

Parallel For Loops

- Often, it is desirable to have a sequence of `for`-directives within a parallel construct that do not execute an implicit barrier at the end of each `for` directive.
- OpenMP provides a clause – `nowait`, which can be used with a `for` directive.

Parallel For Loops: Example

```
#pragma omp parallel
{
    #pragma omp for nowait
        for (i = 0; i < nmax; i++)
            if (isEqual(name, current_list[i])
                processCurrentName(name);
    #pragma omp for
        for (i = 0; i < mmax; i++)
            if (isEqual(name, past_list[i])
                processPastName(name);
}
```

The `sections` Directive

- OpenMP supports non-iterative parallel task assignment using the `sections` directive.
- The general form of the `sections` directive is as follows:

```
#pragma omp sections [clause list]
{
    [#pragma omp section
        /* structured block */
    ]
    [#pragma omp section
        /* structured block */
    ]
    ...
}
```

The `sections` Directive: Example

```
#pragma omp parallel
{
    #pragma omp sections
    {
        #pragma omp section
        {
            taskA();
        }
        #pragma omp section
        {
            taskB();
        }
        #pragma omp section
        {
            taskC();
        }
    }
}
```

Nesting `parallel` Directives

- Nested parallelism can be enabled using the `OMP_NESTED` environment variable.
- If the `OMP_NESTED` environment variable is set to `TRUE`, nested parallelism is enabled.
- In this case, each parallel directive creates a new team of threads.

Synchronization Constructs in OpenMP

OpenMP provides a variety of synchronization constructs:

```
#pragma omp barrier

#pragma omp single [clause list]
         structured block

#pragma omp master
         structured block

#pragma omp critical [(name)]
         structured block

#pragma omp ordered
    structured block
```

OpenMP Library Functions

In addition to directives, OpenMP also supports a number of functions that allow a programmer to control the execution of threaded programs.

```
/* thread and processor count */
void omp_set_num_threads (int num_threads);
int omp_get_num_threads ();
int omp_get_max_threads ();
int omp_get_thread_num ();
int omp_get_num_procs ();
int omp_in_parallel();
```

OpenMP Library Functions

```
/* controlling and monitoring thread creation */
void omp_set_dynamic (int dynamic_threads);
int omp_get_dynamic ();
void omp_set_nested (int nested);
int omp_get_nested ();

/* mutual exclusion */
void omp_init_lock (omp_lock_t *lock);
void omp_destroy_lock (omp_lock_t *lock);
void omp_set_lock (omp_lock_t *lock);
void omp_unset_lock (omp_lock_t *lock);
int omp_test_lock (omp_lock_t *lock);
```

In addition, all lock routines also have a nested lock counterpart for recursive mutexes.

Environment Variables in OpenMP

- `OMP_NUM_THREADS`: This environment variable specifies the default number of threads created upon entering a `parallel` region.

- `OMP_SET_DYNAMIC`: Determines if the number of threads can be dynamically changed.

- `OMP_NESTED`: Turns on nested parallelism.

- `OMP_SCHEDULE`: Scheduling of for-loops if the clause specifies runtime.

Explicit Threads versus Directive Based Programming

- Directives layered on top of threads facilitate a variety of thread-related tasks.
- A programmer is rid of the tasks of initializing attributes objects, setting up arguments to threads, partitioning iteration spaces, etc.
- There are some drawbacks to using directives as well.
- An artifact of explicit threading is that data exchange is more apparent. This helps in alleviating some of the overheads from data movement, false sharing, and contention.
- Explicit threading also provides a richer API in the form of condition waits, locks of different types, and increased flexibility for building composite synchronization operations.
- Finally, since explicit threading is used more widely than OpenMP, tools and support for Pthreads programs are easier to find.