COMP/CS 605: Introduction to Parallel Computing
Lecture 30: OpenMP: Producer/Consumer

Mary Thomas

Department of Computer Science
Computational Science Research Center (CSRC)
San Diego State University (SDSU)

Presented: 04/11/16
Updated: 04/11/16
### Table of Contents

1. **OpenMP: Producer-Consumers**
   - Queing Systems
   - Queue Message Passing
   - Atomic Directive

2. **Critical Sections & Locks**
   - Producer/Consumer Code Example

3. **OpenMP Summary & Conclusions**
Producer-Consumers: Queing Systems
Producer-Consumer Benefit from Use of Queues

Queues

- Can be viewed as an abstraction of a line of customers waiting to pay for their groceries in a supermarket.
- A natural data structure to use in many multithreaded applications.
- For example, suppose we have several “producer” threads and several “consumer” threads.
  - Producer threads might “produce” requests for data.
  - Consumer threads might “consume” the request by finding or generating the requested data.
First in First Out (FIFO) queue

Source: http://en.wikipedia.org/wiki/OpenMP
Using Queues for Message Passing

Message-Passing

- Each thread could have a shared message queue, and when one thread wants to “send a message” to another thread, it could enqueue the message in the destination thread’s queue.

- A thread could receive a message by dequeuing the message at the head of its message queue.
Message-Passing

```
for (sent_msgs = 0; sent_msgs < send_max; sent_msgs++) {
    Send_msg();
    Try_receive();
}

while (!Done())
    Try_receive();
```
Sending Messages

- Any thread can enqueue messages into another thread's queue
- Need to know front/head and back/tail of queue (FIFO)
- Need to develop an Enqueue function
- Critical Block to control access to front/head/and messages (send or recv)
Sending Messages

```plaintext
mesg = random();
dest = random() % thread_count;
# pragma omp critical
Enqueue(queue, dest, my_rank, mesg);
```
Receiving Messages

- Only owner can dequeue messages, so synchronization important.
- Need to develop a Dequeue function that controls access to
- Critical Block to control access to front/head/and messages (send or recv)
  - use two variables count number of messages enqueued and dequeued.
  - \(\text{queue} \_\text{size} = \text{enqueued} - \text{dequeued}\)
A thread is responsible for dequeueing its messages. Other threads can only add messages. Messages added to end and removed from front (FIFO). Synchronization needed after last entry.
Message Queue Data

- list of messages
- pointer to rear of queue
- pointer to front of queue
- count of messages dequeued
Thread Queue Program complete

- When done, threads increments `done_sending`
- This is a critical section: `# pragma omp critical`
- OpenMP has intrinsic function: `# pragma omp atomic`
- Higher performance but limited
Thread Queue Program Startup

- Threads are started with a parallel block directive.
- At start of execution, one thread gets command line arguments.
- Master allocates *array of message queues*: one for each thread.
  - array needs to be shared among the threads
  - any thread can send to any other thread
  - any thread can enqueue a message in any of the queues.
Thread Queue Program Startup

Queue elements:
- list of messages
- pointer index to rear of queue
- pointer index to front of queue
- count of enqueued messages
- count of dequeue messages
Thread Queue Program Startup

- In some cases, one or more threads may finish allocating their queues before some other threads.
- Explicit barrier is needed to block threads until all threads in team have arrived.
- After all the threads have reached the barrier all the threads in the team can proceed.
- Accomplished by using:  
  
  # pragma omp barrier

- When thread is done, it increments its done\_sending variable, which is a critical section.
/* File: queue.c
 * Purpose: Implement a queue of pairs of ints (msg source and content)
 * using a linked list. Operations are Enqueue, Dequeue, Print,
 * Search, and Free.
 * * Compile: gcc -g -Wall -DUSE_MAIN -o queue queue.c
 * Usage: ./queue
 * * Input: Operations (first letter of op name) and, when necessary, keys
 * Output: Prompts for input and results of operations
 * * IPP: Section 5.8.1 (pp. 241 and ff.)
 */
#include <stdio.h>
#include <stdlib.h>
#include "queue.h"

#ifdef USE_MAIN
int main(void) {
    char op;
    int src, msg;
    struct queue_s* q_p = Allocate_queue();
printf("Op? (e, d, p, s, f, q)\n");
scanf(" %c", &op);
while (op != 'q' && op != 'Q') {
    switch (op) {
    case 'e':
    case 'E':
        printf("Src? Mesg?\n");
        scanf("%d%d", &src, &mesg);
        Enqueue(q_p, src, mesg);
        break;
    case 'd':
    case 'D':
        if (Dequeue(q_p, &src, &mesg))
            printf("Dequeued src = %d, mesg = %d\n", src, mesg);
        else
            printf("Queue is empty\n");
        break;
    case 's':
    case 'S':
        printf("Mesg?\n");
        scanf("%d", &mesg);
        if (Search(q_p, mesg, &src))
            printf("Found %d from %d\n", mesg, src);
        else
            printf("Didn’t find %d\n", mesg);
        break;
    case 'p':
    case 'P':
        Print_queue(q_p); break;
    case 'f':
    case 'F':
        Free_queue(q_p); break;
    default:
        printf("%c isn’t a valid command\n", op);
        printf("Please try again\n");
    } /* switch */
    printf("Op? (e, d, p, s, f, q)\n");
    scanf(" %c", &op);
} /* while */
Free_queue(q_p);
free(q_p);
return 0;
} /* main */
struct queue_s* Allocate_queue() {
    struct queue_s* q_p = malloc(sizeof(struct queue_s));
    q_p->enqueued = q_p->dequeued = 0;
    q_p->front_p = NULL;
    q_p->tail_p = NULL;
    return q_p;
} /* Allocate_queue */

/* Frees nodes in queue: leaves queue struct allocated */
void Free_queue(struct queue_s* q_p) {
    struct queue_node_s* curr_p = q_p->front_p;
    struct queue_node_s* temp_p;

    while(curr_p != NULL) {
        temp_p = curr_p;
        curr_p = curr_p->next_p;
        free(temp_p);
    }
    q_p->enqueued = q_p->dequeued = 0;
    q_p->front_p = q_p->tail_p = NULL;
} /* Free_queue */

void Print_queue(struct queue_s* q_p) {
    struct queue_node_s* curr_p = q_p->front_p;

    printf("queue = \n");
    while(curr_p != NULL) {
        printf(" src = %d, mesg = %d\n", curr_p->src, curr_p->mesg);
        curr_p = curr_p->next_p;
    }
    printf("enqueued = %d, dequeued = %d\n", q_p->enqueued, q_p->dequeued);
    printf("\n");
} /* Print_Queue */
void Enqueue(struct queue_s* q_p, int src, int mesg) {
    struct queue_node_s* n_p = malloc(sizeof(struct queue_node_s));
    n_p->src = src;
    n_p->mesg = mesg;
    n_p->next_p = NULL;
    if (q_p->tail_p == NULL) { /* Empty Queue */
        q_p->front_p = n_p;
        q_p->tail_p = n_p;
    } else {
        q_p->tail_p->next_p = n_p;
        q_p->tail_p = n_p;
    }
    q_p->enqueued++;
} /* Enqueue */

int Dequeue(struct queue_s* q_p, int* src_p, int* mesg_p) {
    struct queue_node_s* temp_p;
    if (q_p->front_p == NULL) return 0;
    *src_p = q_p->front_p->src;
    *mesg_p = q_p->front_p->mesg;
    temp_p = q_p->front_p;
    if (q_p->front_p == q_p->tail_p) /* One node in list */
        q_p->front_p = q_p->tail_p = NULL;
    else
        q_p->front_p = temp_p->next_p;
    free(temp_p);
    q_p->dequeued++;
    return 1;
} /* Dequeue */

int Search(struct queue_s* q_p, int mesg, int* src_p) {
    struct queue_node_s* curr_p = q_p->front_p;
    while (curr_p != NULL)
        if (curr_p->mesg == mesg) {
            *src_p = curr_p->src;
            return 1;
        } else {
            curr_p = curr_p->next_p;
        }
    return 0;
} /* Search */
OpenMP Program starts like any sequential program: single threaded

To create additional threads user starts a parallel region

- Additional slave threads are launched to create a team
- Master thread is part of the team
- Threads “go away” at the end of the parallel region: usually sleep or spin

Repeat parallel regions as necessary

- Fork-join model

Source: http://sc.tamu.edu/help/power/powerlearn/presentations/OpenMPnw.ppt
The Atomic Directive (1)

- Unlike the critical directive, it can only protect critical sections that consist of a single C assignment statement.

```c
#pragma omp atomic
```

- Further, the statement must have one of the following forms:
  
  ```c
  x <op>= <expression>;
  x++;
  ++x;
  x--;  
  --x;
  ```
The Atomic Directive (2)

- Here `<op>` can be one of the binary operators
  
  ```
  +, *, -, /, &, ^, |, <<, or >>
  ```

- Many processors provide a special load-modify-store instruction.

- A critical section that only does a load-modify-store can be protected much more efficiently by using this special instruction rather than the constructs that are used to protect more general critical sections.
Atomic Directive

\[ x \langle \text{op} \rangle = \langle \text{expression} \rangle \]

- Only the load and store of \( x \) are guaranteed to be protected
- What happens here?
  
  ```
  #pragma omp atomic
  x += y++
  ```

- \( x \) update is protected: \( \langle \text{op} \rangle \) is a + operation, so it is protected.
- \( y++ \) update may not be safe
// File: queue_lk.c
* Purpose: Implement a queue with locks using a linked list and OpenMP.
* Operations are Enqueue, Dequeue, Print, Search, and Free.
* To be used with omp_msglk.c
* Compile: gcc -g -Wall -DUSE_MAIN -fopenmp -o queue_lk queue_lk.c
* Usage: ./queue_lk
* Input: Operations (first letter of op name) and, when necessary, keys
* Output: Prompts for input and results of operations
* IPP: Section 5.8.9 (pp. 248 and ff.)
*/
#include <stdio.h>
#include <stdlib.h>
#include <omp.h>
#include "queue_lk.h"

printf("Op? (e, d, p, s, f, q)\n"); scanf(" %c", &op); switch (op) {
    case 'e':
    case 'E':
        printf("Src? Mesg?\n"); scanf("%d%d", &src, &mesg);
        omp_set_lock(&q_p->lock);
        Enqueue(q_p, src, mesg);
        omp_unset_lock(&q_p->lock);
        break;
OpenMP: Producer-Consumers

Atomic Directive

case 'd':
case 'D':
    omp_set_lock(&q_p->lock);
    not_empty = Dequeue(q_p, &src, &mesg);
    omp_unset_lock(&q_p->lock);
    if (not_empty)
        printf("Dequeued src = %d, mesg = %d\n", src, mesg);
    else
        printf("Queue is empty\n");
    break;
case 's':
case 'S':
    printf("Mesg?\n"); scanf("%d", &mesg);
    if (Search(q_p, mesg, &src))
        printf("Found %d from %d\n", mesg, src);
    else
        printf("Didn't find %d\n", mesg);
    break;
case 'p':
case 'P':
    Print_queue(q_p); break;
case 'f':
case 'F':
    omp_set_lock(&q_p->lock);
    Free_queue(q_p);
    omp_unset_lock(&q_p->lock);
    break;
    default:
        printf("%c isn't a valid command\n", op); printf("Please try again\n");
    } /* switch */
    printf("Op? (e, d, p, s, f, q)\n"); scanf(" %c", &op);
} /* while */
Free_queue(q_p);
omp_destroy_lock(&q_p->lock);
free(q_p);
return 0;
} /* main */
#endif
OpenMP: Producer-Consumers

Atomic Directive

```c
struct queue_s* Allocate_queue() {
    struct queue_s* q_p = malloc(sizeof(struct queue_s));
    q_p->enqueued = q_p->dequeued = 0;
    q_p->front_p = NULL;
    q_p->tail_p = NULL;
    omp_init_lock(&q_p->lock);
    return q_p;
} /* Allocate_queue */

/* Frees nodes in queue: leaves queue struct allocated and lock * initialized */
void Free_queue(struct queue_s* q_p) {
    struct queue_node_s* curr_p = q_p->front_p;
    struct queue_node_s* temp_p;

    while(curr_p != NULL) {
        temp_p = curr_p;
        curr_p = curr_p->next_p;
        free(temp_p);
    }
    q_p->enqueued = q_p->dequeued = 0;
    q_p->front_p = q_p->tail_p = NULL;
} /* Free_queue */

void Print_queue(struct queue_s* q_p) {
    struct queue_node_s* curr_p = q_p->front_p;

    printf("queue = \n");
    while(curr_p != NULL) {
        printf(" src = %d, mesg = %d\n", curr_p->src, curr_p->mesg);
        curr_p = curr_p->next_p;
    }
    printf("enqueued = %d, dequeued = %d\n", q_p->enqueued, q_p->dequeued);
    printf("\n");
} /* Print_Queue */
```
void Enqueue(struct queue_s* q_p, int src, int mesg) {
    struct queue_node_s* n_p = malloc(sizeof(struct queue_node_s));
    n_p->src = src;
    n_p->mesg = mesg;
    n_p->next_p = NULL;
    if (q_p->tail_p == NULL) { /* Empty Queue */
        q_p->front_p = n_p;
        q_p->tail_p = n_p;
    } else {
        q_p->tail_p->next_p = n_p;
        q_p->tail_p = n_p;
    }
    q_p->enqueued++;
} /* Enqueue */

int Dequeue(struct queue_s* q_p, int* src_p, int* mesg_p) {
    struct queue_node_s* temp_p;

    if (q_p->front_p == NULL) return 0;
    *src_p = q_p->front_p->src;
    *mesg_p = q_p->front_p->mesg;
    temp_p = q_p->front_p;
    if (q_p->front_p == q_p->tail_p) /* One node in list */
        q_p->front_p = q_p->tail_p = NULL;
    else
        q_p->front_p = temp_p->next_p;
    free(temp_p);
    q_p->dequeued++;
    return 1;
} /* Dequeue */

int Search(struct queue_s* q_p, int mesg, int* src_p) {
    struct queue_node_s* curr_p = q_p->front_p;

    while (curr_p != NULL)
        if (curr_p->mesg == mesg) {
            *src_p = curr_p->src;
            return 1;
        } else {
            curr_p = curr_p->next_p;
        }
    return 0;
} /* Search */
Critical Sections

- For the case of multiple critical sections, OpenMP provides the option of adding a name to a critical directive:
  
  \# pragma omp critical(name)

- Parallelism: two blocks protected with critical directives with different names can be executed simultaneously.

- Problem: names are set during compilation - how to set different critical section for each threads queue?

  \implies Locks
OpenMP Locks

- A lock is composed of a *data structure* and *functions* that allow the programmer to explicitly enforce mutual exclusion in a critical section.

- It is shared among threads that will exec critical section
  - one thread will init the lock (e.g. master)
  - other threads will try to enter the block:
    - on success, a thread *obtains* the lock
    - when done the thread will *relinquish* the lock.
  - the last thread using lock will destroy lock

- Two types of locks:
  - *simple*: can only be set once before it is unset
  - *nested*: can be multiple times by same thread before it is unset
### OpenMP Lock Functions

void omp_init_lock(omp_lock_t *lock);

void omp_init_nest_lock(omp_nest_lock_t *lock);
    initializes lock; the initial state is unlocked, for the nestable lock the initial count is zero. These functions should be called from serial portion.

void omp_destroy_lock(omp_lock_t *lock);

void omp_destroy_nest_lock(omp_nest_lock_t *lock); the argument should point to initialized lock variable that is unlocked

void omp_set_lock(omp_lock_t *lock);

void omp_set_nest_lock(omp_nest_lock_t *lock);
    ownership of lock is granted to the thread executing the function; with nestable lock the nesting count is incremented if the (simple) lock is set when the function is executed the requesting thread is blocked until the lock can be obtained
OpenMP Lock Functions

```c
void omp_unset_lock(omp_lock_t *lock);

void omp_unset_nest_lock(omp_nest_lock_t *lock);
    the argument should point to initialized lock in possession of the invoking
    thread, otherwise the results are undefined. For the nested lock the
    function decrements the nesting count and releases the ownership
    when the count reaches 0

int omp_test_lock(omp_lock_t *lock);

int omp_test_nest_lock(omp_nest_lock_t *lock);
    these functions attempt to get the lock in the same way as omp_set_(nest)_lock,
    except these functions are non-blocking

for a simple lock, the function returns non-zero if the lock is
    successfully set, otherwise it returns 0

for a nestable lock, the function returns the new nesting count if the
    lock is successfully set, otherwise it returns 0
```
Locks.

/* Executed by one thread */
Initialize the lock data structure;
...

/* Executed by multiple threads */
Attempt to lock or set the lock data structure;
Critical section;
Unlock or unset the lock data structure;
...

/* Executed by one thread */
Destroy the lock data structure;
OpenMP Lock Functions

Code Example:
#include <omp.h>
.
omp_lock_t *lck;
.
omp_init_lock(lck);
.
/* spin until the lock is granted */
while( !omp_test_lock(lck));
{
  do some work
}
omp_destroy_lock(lck);
.

Using Locks with Queue-based Message-Passing Programs.

```c
#pragma omp critical
/* q_p = msg_queues[dest] */
Enqueue(q_p, my_rank, mesg);

/* q_p = msg_queues[dest] */
omp_set_lock(&q_p->lock);
Enqueue(q_p, my_rank, mesg);
omp_unset_lock(&q_p->lock);
```
Message Queue Structure Data

- list of messages
- pointer to rear of queue
- pointer to front of queue
- count of messages dequeued
- lock variable: `omp_lock_t`
Which is best?

- We have looked at the *critical* and *atomic* directives and *locks*.
- *atomic*: fast because it only does one thing; but OpenMP allows all atomic directives to enforce mutual exclusion across all atomic directives.
- *critical*: easy to use, for multiple they should be named.
- *locks*: performance and function similar to named critical; best used for structures
Caveats

- You shouldn’t mix the different types of mutual exclusion for a single critical section - they don’t share exclusive actions:

```
#pragma omp atomic
x += f(y)  \quad x = g(x)
```

- There is no guarantee of fairness in mutual exclusion constructs.

- It can be dangerous to nest mutual exclusion constructs.

```
#pragma omp critical
y += f(x)
```

```
.....

double f(double x) {
    #pragma omp critical
    z += g(x) /* z is shared */
}```
Caveats (2)

- Can improve things with naming
  ```
  # pragma omp critical(one)
  y  +=  f(x)
  ...
  
  double f(double x) {
    #pragma omp critical(two)
    z  +=  g(x) /* z is shared */
  }
  ```

- but this won’t help in all situations; example of `deadlock`

<table>
<thead>
<tr>
<th>Time</th>
<th>Thread u</th>
<th>Thread v</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Enter crit. sect. <code>one</code></td>
<td>Enter crit. sect. <code>two</code></td>
</tr>
<tr>
<td>1</td>
<td>Attempt to enter <code>two</code></td>
<td>Attempt to enter <code>one</code></td>
</tr>
<tr>
<td>2</td>
<td>Block</td>
<td>Block</td>
</tr>
</tbody>
</table>
Critical Sections & Locks

Producer/Consumer Code Example

Main

/* File: producer_consumer.c
* Purpose: Implement a producer-consumer program in which some of the threads are producers
and others are consumers. The producers read text from a collection of files, one per producer.
They insert lines of text into a single shared queue. The consumers take the lines of text and
tokenize them -- i.e., identify strings of characters separated by whitespace from the rest of the
line. When a consumer finds a token, it writes to stdout.
*/
int main(int argc, char* argv[]) {
    int prod_count, cons_count;
    FILE* files[MAX_FILES];
    int file_count;

    if (argc != 3) Usage(argv[0]);
    prod_count = strtol(argv[1], NULL, 10);
    cons_count = strtol(argv[2], NULL, 10);

    /* Read in list of filenames and open files */
    Get_files(files, &file_count);

    # ifdef DEBUG
    printf("prod_count = %d, cons_count = %d, file_count = %d\n",
           prod_count, cons_count, file_count);
    # endif

    /* Producer-consumer */
    Prod_cons(prod_count, cons_count, files, file_count);

    return 0;
} /* main */
/ * Function:    Prod_cons * Purpose:    Divides tasks among threads */
void Prod_cons(int prod_count, int cons_count, FILE* files[], int file_count) {
    int thread_count = prod_count + cons_count;
    struct list_node_s* queue_head = NULL; struct list_node_s* queue_tail = NULL;
    int prod_done_count = 0;

    #pragma omp parallel num_threads(thread_count) default(none) \
        shared(file_count, queue_head, queue_tail, files, prod_count, \
            cons_count, prod_done_count)
    { int my_rank = omp_get_thread_num(), f;
        if (my_rank < prod_count) { /* Producer code */
            /* A cyclic partition of the files among the producers */
            for (f = my_rank; f < file_count; f += prod_count) {
                Read_file(files[f], &queue_head, &queue_tail, my_rank);
            }
            #pragma omp atomic
            prod_done_count++;
        } else { /* Consumer code */
            struct list_node_s* tmp_node;
            while (prod_done_count < prod_count) {
                tmp_node = Dequeue(&queue_head, &queue_tail, my_rank);
                if (tmp_node != NULL) {
                    Tokenize(tmp_node->data, my_rank);
                    free(tmp_node);
                }
            }
            while (queue_head != NULL) {
                tmp_node = Dequeue(&queue_head, &queue_tail, my_rank);
                if (tmp_node != NULL) {
                    Tokenize(tmp_node->data, my_rank);
                    free(tmp_node);
                }
            }
        }
    } /* pragma omp parallel */
} /* Prod_cons */
Critical Sections & Locks

Producer/Consumer Code Example

Read_file

```c
/**---------------------------------------------------------
 * Function:    Read_file
 * Purpose:     read text line from file into the queue linkedlist
 * In arg:      file, my_rank
 * In/out arg:  queue_head, queue_tail
 */

void Read_file(FILE* file, struct list_node_s** queue_head,
               struct list_node_s** queue_tail, int my_rank) {

    char* line = malloc(MAX_CHAR*sizeof(char));
    while (fgets(line, MAX_CHAR, file) != NULL) {
        printf("Th %d > read line: %s", my_rank, line);
        Enqueue(line, queue_head, queue_tail);
        line = malloc(MAX_CHAR*sizeof(char));
    }

    fclose(file);
} /* Read_file */
```
/**
 * Function: Enqueue
 * Purpose: create data node, add into queue linkedlist
 * In arg: line
 * In/out arg: queue_head, queue_tail
 */
void Enqueue(char* line, struct list_node_s** queue_head, struct list_node_s** queue_tail) {
struct list_node_s* tmp_node = NULL;
tmp_node = malloc(sizeof(struct list_node_s));
tmp_node->data = line;
tmp_node->next = NULL;
#pragma omp critical
if (*queue_tail == NULL) { // list is empty
*queue_head = tmp_node;
*queue_tail = tmp_node;
} else {
(*queue_tail)->next = tmp_node;
*queue_tail = tmp_node;
}
*/ Enqueue */
Dequeue

```c
/* Function: Dequeue
 * Purpose: remove a node from queue linkedlist and tokenize them
 * In arg: my_rank
 * In/out arg: queue_head, queue_tail
 * Ret val: Node at head of queue, or NULL if queue is empty
 */
struct list_node_s* Dequeue(struct list_node_s** queue_head,
                             struct list_node_s** queue_tail, int my_rank) {
    struct list_node_s* tmp_node = NULL;
    if (*queue_head == NULL) // empty
        return NULL;

    # pragma omp critical
    {
        if (*queue_head == *queue_tail) // last node
            *queue_tail = (*queue_tail)->next;

        tmp_node = *queue_head;
        *queue_head = (*queue_head)->next;
    }

    return tmp_node;
} /* Dequeue */
```
OpenMP Summary & Conclusions

Summary and Conclusions

- OpenMP is a standard for programming shared-memory systems.
- OpenMP uses both special functions and preprocessor directives called pragmas.
- OpenMP programs start multiple threads rather than multiple processes.
- Many OpenMP directives can be modified by clauses.
- A major problem in the development of shared memory programs is the possibility of race conditions.
- OpenMP provides several mechanisms for insuring mutual exclusion in critical sections:
  - Critical directives: Named critical directives; Atomic directives; Simple locks
- By default most systems use a block-partitioning of the iterations in a parallelized for loop:
- OpenMP offers a variety of scheduling options.
- In OpenMP the scope of a variable is the collection of threads to which the variable is accessible.
- A reduction is a computation that repeatedly applies the same reduction operator to a sequence of operands in order to get a single result.
OpenMP Interface Model

- **Directives and pragmas**
  - Control structures
  - Work sharing
  - Synchronization
  - Data scope attributes:
    - private
    - firstprivate
    - lastprivate
    - shared
    - reduction
    - Orphaning

- **Runtime library routines**
  - Control and query routines:
    - number of threads
    - throughput mode
    - nested parallelism
  - Lock API

- **Environment Variables**
  - Runtime environment:
    - schedule type
    - max #threads
    - nested parallelism
    - throughput mode
Run Time Library

subroutine omp_set_num_threads(scalar)
 sets the number of threads to use for subsequent parallel region
    integer function omp_get_num_threads()
 should be called from parallel segment. Returns \# of threads currently executing
    integer function omp_get_max_threads()
 can be called anywhere in the program. Returns max number of threads that can
 be returned by omp_get_num_threads()
    integer function omp_get_thread_num()
 returns id of the thread executing the function. The thread id lies in between 0 and
 omp_get_num_threads()-1
    integer function omp_get_num_procs()
 maximum number of processors that could be assigned to the program
    logical function omp_in_parallel()
 returns .TRUE. (non-zero) if it is called within dynamic extent of a parallel region
 executing in parallel; otherwise it returns .FALSE. (0).
    subroutine omp_set_dynamic(logical)
    logical function omp_get_dynamic()
 query and setting of dynamic thread adjustment; should be called only from serial
 portion of the program