Introduction to Parallel Computing

Shared-memory programming with OpenMP

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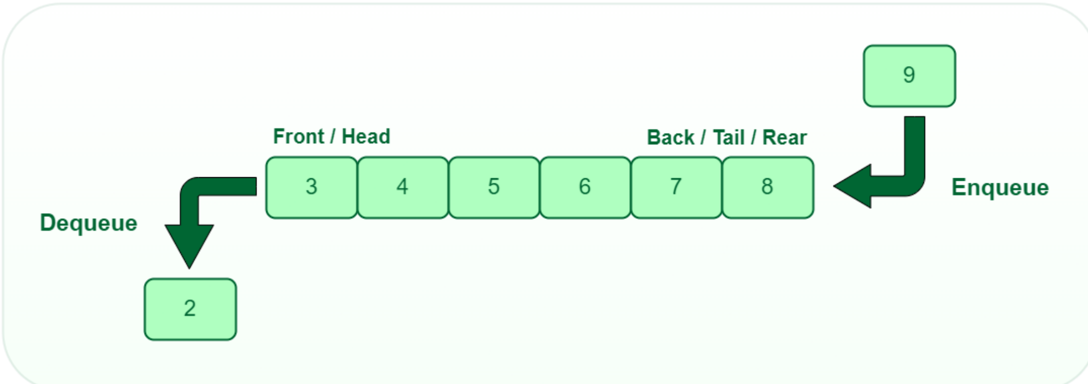
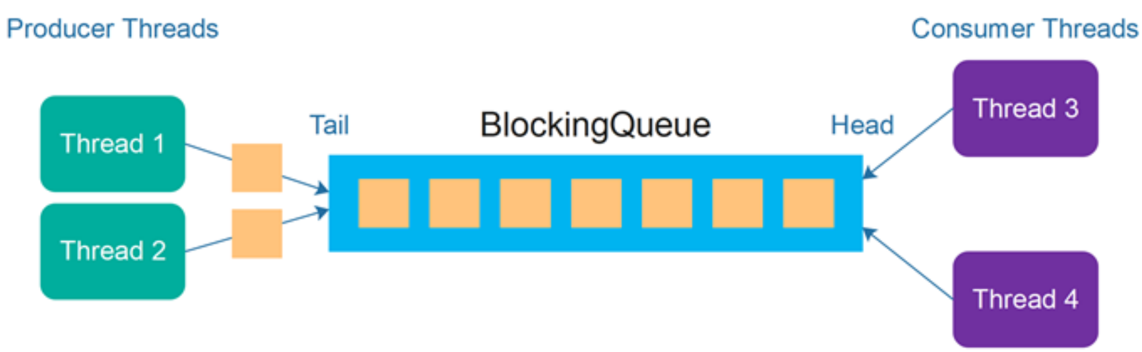
Producers and consumers

- A **queue** is a data structure in which elements are inserted at the rear of the queue and removed from the front of the queue.
  - Adding elements → enqueue
  - Removing elements → dequeue



- Queues appear in many **applications**:
  - Print spooling
  - Operating systems scheduling/task scheduling
  - Data buffers in networking
  - Load balancing in web servers
- Queues are fundamental in **producer-consumer** applications:
  - Part the of the application is **producing** data, and another part is **consuming** the data



- Let's implement a **message-passing** application that is based on the **producer-consumer** pattern.
  - Each thread has a **shared-message queue**.
  - Each thread generates random (integer values) messages and random destination for the messages.
  - A **producer** thread **enqueues** the message in the queue.
  - A **consumer** thread checks if the queue received a message, and then **dequeues** it.
  - Each thread **alternates** between sending and receiving messages.

  - The user will specify the **number of messages** each thread should send.
  - When a thread is **done sending messages**, it receives messages until all the threads are done, at which point all the threads **quit**.
- Pseudocode for each thread might look something like this:

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

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

- Core segments/functions of the program:
  - Sending messages → $Send\_msg()$
  - Receiving messages → $Try\_receive()$
  - Terminating the program → $Done()$

Sending messages

- Accessing a **message queue** to **enqueue** a message is a **critical section**.
  - We need to regulate how threads access the queues to avoid dropping messages.
- To successfully **enqueue** a message, we need a pointer to the **rear** of the queue.
  - When we enqueue a message, we'll update the rear pointer.

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

  - The $Enqueue$ functions handles updating the rear pointer.
  - Note that this allows a thread to send a message to itself.

Receiving messages

- **Only the owner of the queue (that is, the destination thread) will dequeue from a given message queue.**
- If there are at least two messages in the queue, a call to $Dequeue$ **can't conflict** with any calls to $Enqueue$.
- Before $Dequeue$ing the queue, **we must check its size**; if 0, return none. If the size is >=1, then return the element at the front.
  - We store two variables: $enqueued$, which is the number of added elements, and $dequeued$, which is the number of removed elements.

```
    queue_size = enqueued - dequeued;
    if (queue_size == 0) return;
    else if (queue_size == 1)
#       pragma omp critical
        Dequeue(queue, &src, &mesg);
    else
        Dequeue(queue, &src, &mesg);
    Print_message(src, mesg);
```

- The *critical section* is added to prevent other threads from updating the queue when the owner thread is $Dequeue$ing it when it has only one element.

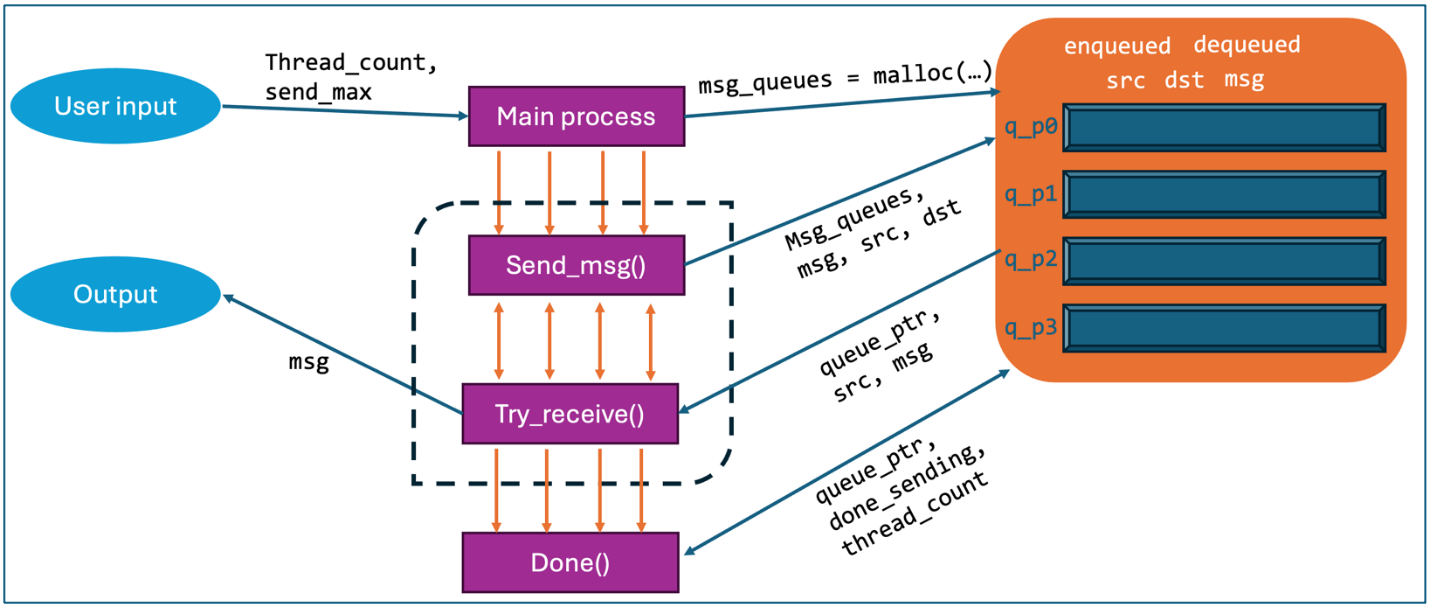
Terminating the program

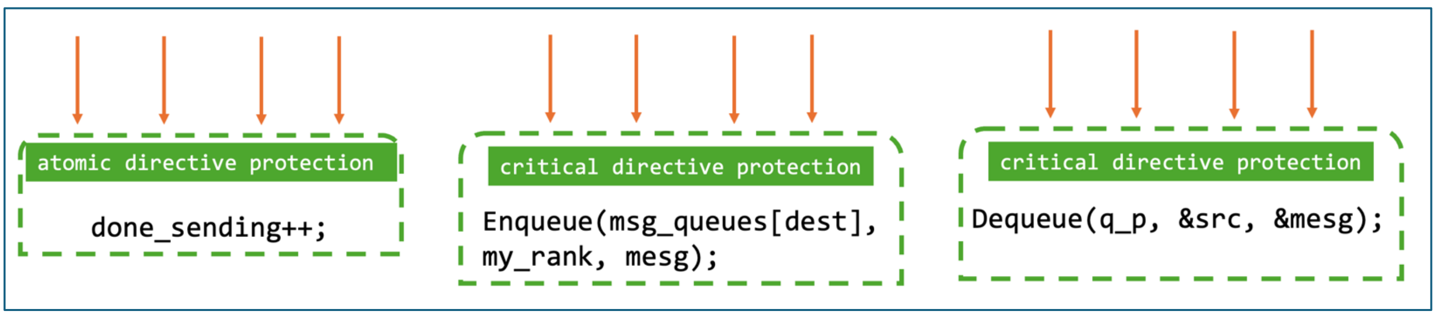
- The **naïve way** to terminate the program (implementing $Done()$) is as follows:

```
queue_size = enqueued - dequeued;
if (queue_size == 0)
    return TRUE;
else
    return FALSE;
```

- The problem with this way is that it is possible that the owner thread compute $queue\_size = 0$, while another thread is adding an element into the queue.
  - Thus, the added message will never be received by the owner thread.
- Instead, we can include $done\_sending$ as a counter variable, so it serves as a flag when all threads have no more messages to send.

```
queue_size = enqueued - dequeued;
if (queue_size == 0 && done_sending == thread_count)
    return TRUE;
else
    return FALSE;
```






```c
#include <stdio.h>
#include <omp.h>
#include <stdlib.h>
#include "queue.h"
// gcc-14 -o prog -fopenmp -DDEBUG omp_msgps.c queue.c

/*-----------------------------------------------------------------*/
void Send_msg(struct queue_s *msg_queues[], int my_rank, int
thread_count, int msg_number) {
    int mesg = -msg_number;
    int dest = random() % thread_count;
#   pragma omp critical
    Enqueue(msg_queues[dest], my_rank, mesg);
    printf("Thread %d > sent %d to %d\n", my_rank, mesg, dest);
}
/*-----------------------------------------------------------------*/
void Try_receive(struct queue_s *q_p, int my_rank) {
    int src, mesg;
    int queue_size = q_p->enqueued - q_p->dequeued;

    if (queue_size == 0) return;
    else if (queue_size == 1)
#      pragma omp critical
        Dequeue(q_p, &src, &mesg);
    else
        Dequeue(q_p, &src, &mesg);
    //printf("Thread %d > received %d from %d\n", my_rank, mesg, src);

}
```

```c
/*------------------------------------------------------------------*/
int Done(struct queue_s *q_p, int done_sending, int thread_count) {
    int queue_size = q_p->enqueued - q_p->dequeued;
    if (queue_size == 0 && done_sending == thread_count)
        return 1;
    else
        return 0;
} /* Done */
/*------------------------------------------------------------------*/
int main(int argc, char *argv[]) {
    int thread_count;
    int send_max;
    struct queue_s **msg_queues;
    int done_sending = 0;

    thread_count = 4;
    send_max = 5;

    msg_queues = malloc(thread_count * sizeof(struct queue_node_s *));

#  pragma omp parallel num_threads(thread_count) \
      default(none) shared(thread_count, send_max, msg_queues,
done_sending)
    {
        int my_rank = omp_get_thread_num();
        int msg_number;
        srandom(my_rank);
        msg_queues[my_rank] = Allocate_queue();

#     pragma omp barrier /* Don't let any threads send messages  */
        /* until all queues are constructed     */

        for (msg_number = 0; msg_number < send_max; msg_number++) {
            Send_msg(msg_queues, my_rank, thread_count, msg_number);
            Try_receive(msg_queues[my_rank], my_rank);
        }

   // done_sending is a critical section
  // using atomic instead of critical section has a better performance
#     pragma omp atomic
        done_sending++;

        while (!Done(msg_queues[my_rank], done_sending, thread_count))
            Try_receive(msg_queues[my_rank], my_rank);

     /* My queue is empty, and everyone is done sending             */
     /* So my queue won't be accessed again, and it's OK to free it */
        Free_queue(msg_queues[my_rank]);
        free(msg_queues[my_rank]);
    } /* omp parallel */

    free(msg_queues);
    return 0;
} /* main */
```

- When the program begins execution, the master thread will get command-line arguments and allocate an array of message queues, one for each thread.
- This array needs to be shared among the threads, since any thread can send to any other thread, and hence any thread can enqueue a message in any of the queues.
- We use $omp\ barrier$ to add an explicit barrier so that no thread starts enqueuing or dequeuing until all threads have constructed their queues to avoid errors.
- After completing its sends, each thread increments $done\_sending$ before proceeding to its final loop of receives.
    - Incrementing $done\_sending$ is a **critical section**, and we could protect it with a $\boldsymbol{critical}$ **directive**.
    - Instead, we use **a higher performance directive**, $omp\ atomic$
- $omp\ atomic$ can only **protect** statements with **a single assignment**.
- For example, $\boldsymbol{omp\ atomic}$ protect statements of the following form:

```
x <op>= <expression>;
x++;
++x;
x--;
--x;
```

    - $<expression>$ **must not reference** x
    - $<op>$ can be +, $*$, −, /, &, ^, |, <<, or >>
- $atomic$ directive has special for $\boldsymbol{load - modify - store}$ instructions in modern processors, which is **more efficient** than $critical\ section$

Experiments

1. Run the program as is – with **4 threads and 5 messages** to send and check the output.
    a. You will see that each thread must **send exactly 5 messages**.
    b. Threads **may or may not** receive 5 messages.
2. **Remove the critical section** from the $Try\_receive$ function and run the program **with 4 threads and 5 messages**. The $Try\_receive$ function should look like this:

```c
/*-------------------------------------------------------------------*/
void Try_receive(struct queue_s *q_p, int my_rank) {
    int src, mesg;
    int queue_size = q_p->enqueued - q_p->dequeued;
    if (queue_size == 0) return;
        Dequeue(q_p, &src, &mesg);
    //printf("Thread %d > received %d from %d\n", my_rank, mesg, src);

} /* Try_receive */
```

    a. **The program works fine without any issues.**

3. **Revert the $\boldsymbol{Try\_receive}$ function** and run the program with **10 threads and 10000** messages.
    a. You notice that the program may **take a little longer, but it finishes successfully.**
4. **Remove the critical section** again from $Try\_receive$ and run the program **with 10 threads and 10000 messages.**
    a. **It will either run for ever or it will crash because of heap errors.**

```
prog(11076,0x16b79b000) malloc: Heap corruption detected, free list is damaged at 0x60000004ebf0
*** Incorrect guard value: 0
Thread 5 > sent -1063 to 4
Thread 4 > sent -1012 to 5
Thread 3 > sent -1097 to 1
prog(11076,0x16bdbf000) malloc: *** error for object 0x60000004c3e0: pointer being freed was not allocated
prog(11076,0x16bdbf000) malloc: *** set a breakpoint in malloc_error_break to debug
Thread 0 > sent -1149 to 5
prog(11076,0x1eb99c840) malloc: *** error for object 0x60000004c350: pointer being freed was not allocated
przsh: abort      ./prog
```

5. Run the **same program** but with **100 threads and 100,000 messages**.
    a. The program is **very likely** to run for ever.
6. **Revert the $\boldsymbol{Try\_recieve}$ function** and run with **100 threads and 100000** messages.
    a. The program **takes a few minutes** and **finishes successfully**.

- *These experiments demonstrate the importance of handling **special edge-cases**, in which the termination of a thread/program is dependent on state of the object (whether the queue is empty or not). With small inputs (e.g., 4 threads and 5 messages) errors **may not** occur. But when the problem size's increases (10 threads and 100000 messages) problems occur and hard to detect.*
- Go through the same program but with the textbook version.

Update

Why do use $\boldsymbol{done\_sending}$?

- As we have seen in the previous experiments, $\#pragma\ omp\ critical$ at $Dequeue$ when $queue\_size == 1$ prevents some unexpected errors during the program run.
- So, the critical section in $Try\_receive$ ensures the owner thread removing the last element from the queue. Hence, no other threads are adding elements to the queue at the same time.
- $\therefore critical =$ do not violate the inner workings of the queue.
- On the other hand, the variable $done\_sending$ prevents the thread from terminating **even if the queue is empty**. Other threads might be on their way sending a message to the '*about to terminate*' thread.
- So, $done\_sending$ guarantees no messages are missed.
- $\therefore done\_sending =$ do not leave early.

Try the following experiment:

- Cancel the $done\_sending$ variable and its condition.
- Count the total number of messages sent and received by each thread.

```c
void Send_msg(struct queue_s* msg_queues[], int my_rank, int thread_count, int msg_number,
int *msgs_snd) {
   int mesg = -msg_number;
   int dest = random() % thread_count;
#  pragma omp critical
   Enqueue(msg_queues[dest], my_rank, mesg);
   msgs_snd[my_rank]+=1;
}  /* Send_msg */

void Try_receive(struct queue_s* q_p, int my_rank, int *msgs_rcvd) {
   int src, mesg;
   int queue_size = q_p->enqueued - q_p->dequeued;

   if (queue_size == 0) return;
   else if (queue_size == 1)
#     pragma omp critical
      Dequeue(q_p, &src, &mesg);
   else
      Dequeue(q_p, &src, &mesg);
   msgs_rcvd[my_rank] += 1;
}   /* Try_receive */

int Done(struct queue_s* q_p, int done_sending, int thread_count) {
   int queue_size = q_p->enqueued - q_p->dequeued;
   if (queue_size == 0)// && done_sending == thread_count)
      return 1;
   else
      return 0;
}   /* Done */

int main(int argc, char* argv[]) {
   int thread_count =4;
   int send_max = 5;
   struct queue_s** msg_queues;
   int done_sending = 0;
   int msgs_rcvd[thread_count];
   int msgs_snd[thread_count];
   for (int i = 0; i < thread_count; i++) {
      msgs_rcvd[i] = 0;
      msgs_snd[i] = 0;
}

   msg_queues = malloc(thread_count*sizeof(struct queue_node_s*));

#  pragma omp parallel num_threads(thread_count) \
   default(none) shared(thread_count, send_max, msg_queues, done_sending, msgs_rcvd,
msgs_snd)
   {
      int my_rank = omp_get_thread_num();
      int msg_number;
      srandom(my_rank);
      msg_queues[my_rank] = Allocate_queue();

#     pragma omp barrier

      for (msg_number = 0; msg_number < send_max; msg_number++) {
         Send_msg(msg_queues, my_rank, thread_count, msg_number,  msgs_snd);
         Try_receive(msg_queues[my_rank], my_rank, msgs_rcvd);}

// #     pragma omp atomic
//       done_sending++;

      while (!Done(msg_queues[my_rank], done_sending, thread_count))
         Try_receive(msg_queues[my_rank], my_rank, msgs_rcvd);

      Free_queue(msg_queues[my_rank]);
      free(msg_queues[my_rank]);
   }  /* omp parallel */

   for (int i = 0; i < thread_count; i++) {
      printf("Thread %d sent %d msgs\n", i, msgs_snd[i]);
      printf("Thread %d received %d msgs\n", i, msgs_rcvd[i]);
}
   free(msg_queues);
   return 0;
}  /* main */
```

- You will notice that the program sends a total of 20 messages.
- But the total number of received messages is less than 20!

Imagine this timeline of events:

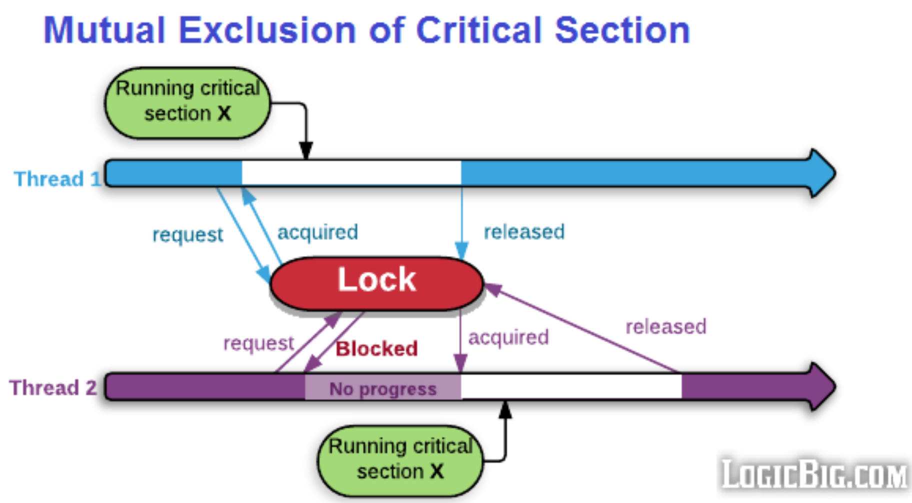
- Thread 0 finishes its for loop, sees its queue is empty. It thinks: “Okay, I’m done.”
- But Thread 1 is still sending messages, and one is en route to Thread 0.
- Without $done\_sending$, Thread 0 might exit, and now Thread 1's message is lost!
- Meanwhile, inside $Try\_receive$, Thread 0 checks its queue:
    - If there’s only one message, it uses a $critical$ section to safely dequeue it.
    - This **avoids race conditions** on the last item in the queue.

Locks

- As an alternative to $critical$ sections, we can use $\boldsymbol{Locks}$.
- A $lock$ consists of a **data structure/functions** enforce mutual exclusion on data or resources.
- Defining locks follows this pseudocode:

```
/* 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;
```

    - $lock$ is **shared among the threads** that will execute the critical section.
    - **One** of the threads will **initialize** the lock.
    - **One** of the threads will **destroy** the lock.
    - A thread entering the critical section will $\boldsymbol{set}$ the lock.
    - When the thread finishes the critical section, it $\boldsymbol{release}$ or $\boldsymbol{unset}$ the lock.
- How locks achieve mutual exclusion:



- Locks in OpenMP:

Action	Function
Initialize a lock	`void omp_init_lock (omp_lock_t* lock_p);`
Acquire a lock	`void omp_set_lock (omp_lock_t* lock_p);`
Release a lock	`void omp_unset_lock (omp_lock_t* lock_p);`
Remove a lock	`void omp_destroy_lock (omp_lock_t* lock_p);`

Using locks in the message-passing program

- In the previous program, we used ***critical* directive** to enforce a mutually exclusive access to a **shared resource**.
    - `done_sending++;`
    - `Enqueue(q_p, my_rank, mesg);`
    - `Dequeue(q_p, &src, &mesg);`
- There is one efficiency issue with this critical section: the *critical* directive **blindly** allows only one thread to **Enqueue** or **Dequeue**.
- But we don't need to block threads that **don't conflict with each other**: for instance, it's safe for **thread 0** to enqueue a message in **thread 1's queue** at the same time that **thread 1** is enqueuing a message in **thread 2's queue**.
    - **So, the *critical* directive allows only one thread do *enqueue*ing at a time regardless the process causes conflicts or not.**
- To **overcome** this, we use *locks* and instead of making the **whole function** of *enqueue* or *dequeue* a **critical section**, we will make the **corresponding queues only critical sections.**
- So, we can do the following:

```
#  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);
```

```
#  pragma omp critical
/* q_p = msg_queues[my_rank] */
Dequeue(q_p, &src, &mesg);
```

→

```
/* q_p = msg_queues[my_rank] */
omp_set_lock(&q_p->lock);
Dequeue(q_p, &src, &mesg);
omp_unset_lock(&q_p->lock);
```

- **Check the source code** in *queue_lk.h*, *queue_lk.c*, and *omp_msglk.c*.
    - **The *lock* is defined as a data member in the *queue* struct.**
- Now when a thread tries to send or receive a message, it can only be **blocked** by a thread accessing the **same message queue**, since **different message queues have different locks**.

In previous implementation, **only one thread** could **send** at a time, regardless of the destination.