Operating Systems – 234123

Homework Exercise 3 – Wet

Teaching Assistant in charge:

Mohammad Agbarya

Assignment Subjects & Relevant Course material

Synchronization, Threads

Recitations 7-8, Lectures 6-7

Assignment Objectives

The objective of this assignment is to give you hands-on experience with parallel programming and various synchronization methods. You are going to implement a synchronization primitive (Barrier) in the first part and in the second part you are required to implement a thread-safe list using some synchronization primitives.

Part I – Reusable Barrier

Introduction

An N-process barrier is a synchronization mechanism that allows N threads, where N is a fixed number, to wait until all of them have reached a certain point. Once all threads have reached this certain point (the barrier), they may all continue. A reusable barrier is a barrier that can be used more than once in the same code, i.e., it could be used to wait until all the N threads reach a certain point, release them to continue and then to reuse it in a following code line to wait for all the N threads to reach that point and then to release them.

For example, we can use barriers to synchronize N people who watch a movie, if each person runs the following thread:

```
buy_popcorn();
buy_something_to_drink();
// wait for everyone else before we start the movie
barrier.wait();
watch_the_movie();
// wait until everyone leaves the cinema
barrier.wait();
close_the_door();
```

In the above example, each thread that calls `barrier.wait()` blocks until the last thread enters the synchronization barrier, and only then all threads are released. Note that the same barrier is used twice to synchronize all threads (which means it is reusable), so once a thread unblocks, it can re-enter the barrier and block again.

Implementation Requirements

Implement the following Barrier API, as defined in the provided `Barrier.h` header file:

1. **`Barrier(unsigned int num_of_threads)`**`;`
    - This is the constructor of the Barrier. it receives one parameter `num_of_threads` – which is the number of threads that this barrier is supposed to handle.
    - Return value: A Barrier Object.

2. **`void Barrier::Wait()`**`;`

- Block and wait until N threads reach this point.
  If you're the Nth thread to call this method wake up the rest of the threads else, block.
- Parameters: none.
- Return value: none.

3. **`~Barrier();`**
   - This is the destructor of the Barrier. destroys or releases any resources that it used (like semaphores and mutexes)
   - Parameters: none.
   - Return value: none.

Important Notes and Tips

- **Don't modify the signatures of the methods defined in the Barrier.h header file.** We will test your code according to this interface.
- You may add any class members you need (integers, Boolean, data structures, …), but **your implementation should use only the following synchronization primitives: semaphores and mutexes.**
  To put it another way, you are not allowed to use any of the following types and their associated functions: `pthread_cond_t`, and obviously not `pthread_barrier_t`.
- You can use as many semaphores as you need.
- In your implementation, you can ignore any errors that the semaphore and mutex functions may return. For instance, according to the man pages, `sem_init()` returns the value EINVAL when the initial value of the semaphore exceeds SEM_VALUE_MAX; we will not check such cases in our tests.
- Use only standard POSIX threads and synchronization functions. You are not allowed, of course, to use the C++11 thread support or the C++11 atomic operations libraries.
- You should try to make your implementation as concurrent and as efficient as possible. The performance of your solution can affect your grade. However, efficiency must not come at the cost of correctness!
- **Make sure your code is running on your virtual machine that you have installed and used in previous homeworks.**

Part II – Thread Safe Linked List

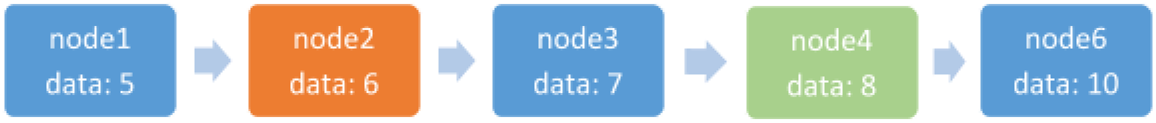
Introduction

In this part you will implement multi-threaded **sorted** linked list (aka thread safe sorted linked list). Each node of the list has a **unique** field **data** which can be considered as the node key, (a situation when two nodes have same data value is not allowed) that is used to keep the list sorted in an increasing order.

In your implementation of the list you can add additional fields to the node structure.

In order to keep high concurrency, you will use fine-grained locking. Multiple operations should be able to run simultaneously but are expected to run normally and do not disturb each other. You must use **hand over hand locking** to achieve that goal.

What is hand over hand locking?
The insertion and removal operations may be called concurrently. Operations involving different elements should not wait for each other unless this is strictly necessary. For example, let's look at the following case:



Let's say we want to do the following operations:

- delete node 2 (orange) with data 6
- insert a new node **after** node 4 (green)

then we should be able to do both operations concurrently.

This means that you cannot use a single lock for the entire list. **Therefore, you must have a separate lock for each element in the list.**
Implementation that locks the entire list to insert or remove a value will not be accepted.

Instead, you should use **hand-over-hand** locking. Hand-over-hand locking is a method of locking elements in a linked structure (such as a linked list), where a previous lock is kept while the next one is being acquired. Going back to our example above, Hand over hand locking would mean, while traversing the list, we should lock the current node and lock the next one before transitioning to the next node. And in removal of node 2 (orange) we should keep locking node 1 and lock node 2 until we free it and update node 1. (similar idea for insertion).

You can find an illustration (and some sample code in java) at
http://fileadmin.cs.lth.se/cs/education/eda015f/2013/herlihy4-5-presentation.pdf
p.s. don't worry about the number of pages :) it's mostly (if not all) animation.

Implementation Requirements
Implement the following List API, as defined in the provided `ThreadSafeList.h` header file (your implementation should be added to `ThreadSafeList.h` header file and you should not add a new source file that implements the header). You can assume that T—the template parameter—will be used only as a primitive/built-in type (e.g., int/double/…):

1. **`List();`**
    - This is the constructor of our thread safe sorted List.

- If some operation fails print to std::cerr the following line and exit(-1)

```
“<function name>: failed”
```

- Return value: List object.

2. **`bool insert(const T& data);`**
    - Insert new node to list **while keeping the list ordered in an ascending order**. If there is already a node that has the same data as @param data then return false (without adding it again), use hand over hand locking.
    - Parameters:
        i. data: the new data to be added to the list
    - Returns true if a new node was added and false otherwise

3. **`bool remove(const T& value);`**
    - Remove the node that its data equals to **value.**
    - Parameters
        i. value the data to lookup a node that has the same data to be removed
    - Returns true if a matched node was found and removed and false otherwise.

4. **`unsigned int getSize();`**
    - Returns the current size of the list.
    - You can’t use global locking here either (coarse grained locking not allowed). (Hint: but you can maintain a counter)

5. **`~List();`**
    - Destructor to our list, destroy / free any resources that it took.
    - You can assume destroy operations are successful (print some error message to stderr for your own debugging in case destroy operations fail)
    - Parameters: none.
    - Return value: none.

6. **`void print();`**
    - Prints the list in an unsafe way. This method is already implemented and provided to you as part of the ThreadSafeList.h header file. This method will be used in some of our tests to test your implementation (to print the final state of the list).
    - You **<u>should not</u>** modify or remove this method from your submitted file.
    - Please note that this method prints a list that has no dummy node. If you decide to add a dummy node to your list implementation then it’s your sole responsibility to adapt the print method to ignore the dummy node without breaking the print method or modifying its behaviour (some of our tests rely on the print format, so please be aware of that).

Special methods:

7. **`virtual void __insert_test_hook() {}`**
8. **`virtual void __remove_test_hook() {}`**

Those are test hooks to be used for testing your code and your hand-over-hand implementation (you can take a look into testListHooks.cpp source file which uses them).

Very important Notes:

- You **<u>should not</u>** modify or remove these methods in your submitted file.
- You should call **`__insert_test_hook()`** inside your insert method, after adding the new node and before releasing the lock(s) (i.e., ***<u>should be called inside the critical section right before the unlock</u>***(s)).
- You should call **`__remove_test_hook()`** inside your remove method, after removing the given node and before releasing the lock(s)) (i.e., ***<u>should be called inside the critical section right before the unlock</u>***(s)).
- Note that the **`__insert_test_hook()`** and **`__remove_test_hook()`** should be called only if the insert and remove methods succeed.
- **Here is a pseudo code shows how to add the hooks in your code:**

```
Insert(data){
    Lock()
    //insert new node
    // if ant error occurred/detected don’t call the hook but instead
    // release any locks and return false indicating that insert was
    // failed
    __insert_test_hook()
    Unlock()
}
Remove (value) {
    Lock()
    //remove the corresponding node
    // if ant error occurred/detected don’t call the hook but instead
    // release any locks and return false indicating that remove was
    // failed
    __remove_test_hook()
    Unlock()
}
```

- **How to use the test hooks and write your own tests based on these two hooks:**
    - These hooks should not be modified in your List class and should keep them as is.
    - You should call the __insert_test_hook() in the critical section of the insert method, right after adding the new node and before releasing the lock. And you should call __remove_test_hook() in the critical section of the remove method, right after removing the required node and before releasing the lock.
    - These two test hooks can be used by overriding them as in we did in the testListHooks.cpp (which was provided to you as a sample code of how to test your hand-over-hand implementation).

- **So how do these hooks work?**
    - Let's suppose that we have a list with the following values/nodes: 2,4,6,8,10,12
        - and we would like to add a new node with a value=11, this node will be added while holding two locks on two different nodes which are 10 and 12 → {2,4,6,8,10,12}.
        - While we hold these two locks we should call the __insert_test_hook().
        - Let's suppose that we want to implement the __insert_test_hook() to simply add an additional node with the value=5
        - For doing that, you should traverse the list, using hand-over-hand locking, starting from its head until you get to the right place to add it.
        - The __insert_test_hook() will call insert(5) which will first lock the nodes 2 and 4 → {2,4,6,8,10,12},
        - then move the lock of 2 to 6 and do the insertion → {2,4,6,8,10,12}.
        - This insertion operation could be done thanks to hand-over-hand locking. That means, if you have a global lock then it's not possible to call insert in parallel with another call of insert while holding the global lock.
    - If you are going to add your own tests using the hooks then please note not to get a deadlock, for example,
        - as in the previous example if you call insert(3) → {2,4,6,8,10,12}
        - and from the __insert_test_hook you try to call insert(13) then you will get a deadlock because insert(3) holds two locks on nodes 2 and 4 which will prevent the hook from traversing the list.

Important Notes and Tips

- **Don't modify the signatures of the methods defined in the ThreadSafeList.h header file.** We will test your code according to this interface.

- Start implementing a sorted linked list (with no locks), test it, make sure that it is working as expected, and only then start applying the hand over hand locking.

- Use thread sanitizers to debug your multi-threaded implementation. You can read more about ThreadSanitizer for C++ here:

  https://github.com/google/sanitizers/wiki/ThreadSanitizerCppManual

- You may add any class members you need (integers, Boolean, data structures, …), but **your implementation should use only mutexes as synchronization primitives.** To put it another way, you are not allowed to use semaphores or any synchronization primitives (other than `pthread_mutex_t`) that are provided in the pthread library.

- You can use as many mutexes as you need.
- In your implementation, you can ignore any errors that the pthreads functions may return; we will not check such cases in our tests.
- Use only standard POSIX threads and synchronization functions. You are not allowed, of course, to use the C++11 thread support or the C++11 atomic operations libraries.
- You should try to make your implementation as concurrent and as efficient as possible. You must use hand over hand locking mechanism when inserting or removing from the list. The performance of your solution can affect your grade. However, efficiency must not come at the cost of correctness!
- You should implement the list API mentioned above in the ThreadSafeList.h header file (and not in separated source file) since we are going to build your code with the following command line:

  ```
  g++ --std=c++11 -pthread -Wall -pedantic -Werror -fPIC
  testthreadSafeList.cpp -o tsl
  ```
- We will build your Barrier code with the same compiler flags mentioned above, i.e.:

  ```
  g++ --std=c++11 -pthread -Wall -pedantic -Werror -fPIC
  testBarrier.cpp Barrier.cpp Barrier.h -o testBarrier
  ```
- **Make sure your code is running on our virtual machine that you have installed in HW0.**

Questions & Answers / Piazza

- The Q&A for the exercise will take place at a public forum Piazza **only**. Please **DO NOT** send questions to the private email addresses of any of the TAs.
- Critical updates about the HW will be published in **pinned** notes in the piazza forum. These notes are mandatory, and it is your responsibility to stay updated.
- Read **previous Q&A** carefully before asking the question; repeated questions will probably go without answers.
- Be **polite**, remember that course staff does this as a service for the students.
- You're not allowed to post any kind of solution and/or source code in the forum as a hint for other students; In case you feel that you must discuss such a matter, please come to the reception hours.
- When posting questions regarding **hw3**, put them in the **hw3** folder

Late Days

- Please **DO NOT** send postponement requests to the TA responsible for this assignment.

Only the **TA in charge** can authorize postponements. In case you need a postponement, please fill out the attached form :

https://docs.google.com/forms/d/171TPPZSpFGlxBt2bGK7zU-Id4rf6B4LYTgKuOqEJSgo

Submission

- You should edit and submit all source files (including headers) that were provided in the course website under the "HW3 Wet" section.
- You should electronically submit a zip file that contains the above files.
- We only require you to submit the implementation of your classes, but not any test programs that use these classes. Of course, this does not mean you will not need a test program for debugging!
- You should not submit a printed version of the source code. However, you should document your source code!
- A file named submitters.txt which includes the ID, name and email of the participating students. The following format should be used:

```
Linus Torvalds linus@gmail.com 234567890
Ken Thompson ken@belllabs.com 345678901
```

- **Important Note:** the zip should contain only the following files (no subdirectories):

```
zipfile -+
|
         +- Barrier.h
         +- Barrier.cpp
         +- ThreadSafeList.h
         +- submitters.txt
```

- You can create the zip by running the following command line:

```
zip ID1_ID2.zip Barrier.h Barrier.cpp ThreadSafeList.h
submitters.txt
```

- If you missed a file and because of this, the exercise is not working, **you will get 0 and resubmission will cost 10 points.** In case you missed an important file (such as the file with all your logic) we may not accept it at all. In order to prevent it you should open the zip file in a new directory and try to build and test your code in the new directory, to see that it behaves as expected.

- **Important Note:** when you submit, **retain your confirmation code and a copy of the file(s)**, in case of technical failure. Your confirmation code is **the only valid proof** that you submitted your assignment when you did.

Have a Successful Journey,
The course staff