OS 2021 – Exercise 3
MapReduce - Multi-threaded Programming

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Due: **10/06/2021**

As stated in the guidelines, the deadline will not be extended

Note: This exercise takes a lot of time. Start early!

High Level Overview

Performance is the major motivation for multi-threaded programming. Multiple processors can execute multiple threads at the same time and do the same amount of computations in less time than it will take a single processor.

Two challenges complicate multi-threaded programming:

1) In many cases it is difficult to split the big task into small parts that can run in parallel.
2) Running in multiple threads requires synchronisation and communication between threads. This introduces an overhead which without careful design can increase the total runtime significantly.

Over the years, several designs were proposed in order to solve these challenges. In this exercise we will implement one of these designs, named MapReduce.

MapReduce is used to parallelise tasks of a specific structure. Such tasks are defined by two functions, ***map*** and ***reduce***, used as follows:

1) The input is given as a sequence of elements.
2) (Map phase) The *map* function is applied to each input element, producing a sequence of intermediary elements.
3) (Sort/Shuffle phases) The intermediary elements are sorted into new sequences (more on this later).
4) (Reduce phase) The *reduce* function is applied to each of the sorted sequences of intermediary elements, producing a sequence of output elements.
5) The output is a concatenation of all sequences of output elements.

Example (From TA6): counting character frequency in strings

1) The input is a sequence of strings.
2) (Map phase) In each string we count how many times each character appears and then produce a sequence of the results.
3) (Sort/Shuffle phases) We sort the counts according to the character, creating new sequences in the process. Now for every character we have a sequence of all counts of this character from all strings.
4) (Reduce phase) For each character we sum over its respective sequence and produce the sum as a single output.
5) The output is a sequence of the sums.

Design

The implementation of this design can be split into two parts:

1) Implementing the functions *map* and *reduce*. The functions implementation will be different for every task. We call this part the client.
2) Implementing everything else – the partition into phases, distribution of work between threads, synchronisation etc. This will be identical for different tasks. We call this part the framework.

Using this split, we can code the framework once and then for every new task, we can just code the significantly smaller and simpler client. In other words, after you have written the code for the framework you can write different map and reduce function depending on the task you would like to perform.

Constructing the framework is the main goal of this exercise and you will have to **implement the framework**. In the next sections we will break this goal down into subgoals and provide a more detailed design for you to implement.

Client Overview

The client contains two main functions: map and reduce.
Since the elements after the map and reduce function should have linear order, every element must have a key that allows us to compare elements and sort them. For this reason, each element is given as a pair (key, value).

We have three types of elements, each having its own key type and value type:

1) Input elements – we denote their key type *k1* and value type *v1*.
2) Intermediary elements – we denote their key type *k2* and value type *v2*.
3) Output elements – we denote their key type *k3* and value type *v3*.

The map function receives a key of type *k1* and a value of type *v1* as input and produces pairs of (*k2*, *v2*).

The framework sort/shuffle phase sort the intermediary elements that created by the map function according to their keys and then create new sequences such that *reduce* will run exactly once for each *k2*.

The reduce function receives a sequence of pairs (*k2*, *v2*) as input, where all keys are identical, and produces pairs of (*k3*, *v3*).

A header *MapReduceClient.h* and a sample client are provided with this exercise.
SampleClient.cpp implement the counting characters frequency in strings example from TA6.
An implementation of a client header *MapReduceClient.h* contains the following:

1) Key/Value classes inheriting from *K1*, *K2*, *K3* and *V1*, *V2*, *V3* including a < operator for the keys, to enable comparison between different elements.
2) The *map* function with the signature:

   ```
   void map(const K1* key, const V1* value, void* context) const
   ```

   This function will intermediate pairs and will add them to the framework databases using the framework function emit2(K2, V2, context).

The context argument is provided to allow *emit2* to receive information from the function that called *map*.s

3) The *reduce* function with the signature:

```
void reduce(const IntermediateVec* pairs, void* context) const
```

IntermediateVec is of type std::vector<std::pair<K2*,V2*>>

All pairs in the vector are expected to have the same key (but not necessarily the same instances of K2).

This function will produce output pairs and will add them to the framework databases using the framework function emit3(K3, V3, context).

The context argument is provided to allow *emit3* to receive information from the function that called *reduce*.

Pay attention that the map and reduce function are called within the framework and the input to these functions is passed by the framework.

Framework Interface Overview

The framework will support running a MapReduce operations as an asynchrony **job**, together with ability to query the current state of a job while it is running. A header *MapReduceFramework.h* is provided with the exercise.

Two types of variables are used in the header to monitor MapReduce job:

1. *JobState* - a struct which quantizes the state of a job, including:
   - stage_t stage – an enum (0-Undefined, 1-Map, 2-Shuffle, 3-Reduce)
     - We will save the job stage using that enum.
       The job should be at an undefined stage until the first thread starts the map phase.
   - float percentage – job progress of current stage (i.e., the percentage of elements that were processed out of all the elements that should be processed in the stage).
2. JobHandle – void*, an identifier of a running job. Returned when starting a job and used by other framework functions (for example to get the state of a job).

The framework interface consists of six functions:

1) startMapReduceJob – This function starts running the MapReduce algorithm (with several threads) and returns a JobHandle.

```
JobHandle startMapReduceJob(const MapReduceClient& client,
const InputVec& inputVec, OutputVec& outputVec, int multiThreadLevel);
```

client – The implementation of *MapReduceClient* or in other words the task that the framework should run.

inputVec – a vector of type std::vector<std::pair<K1*, V1*>>, the input elements.

outputVec – a vector of type std::vector<std::pair<K3*, V3*>>, to which the output elements will be added before returning. You can assume that outputVec is empty.

multiThreadLevel – the number of worker threads to be used for running the algorithm. You will have to create threads using c function pthread_create. You can assume multiThreadLevel argument is valid (greater or equal to 1).

Returns - The function returns JobHandle that will be used for monitoring the job.

You can assume that the input to this function is valid.

2) waitForJob – a function gets JobHandle returned by *startMapReduceFramework* and waits until it is finished.

```
void waitForJob(JobHandle job)
```

Hint – you should use the c function pthread_join.
It is legal to call the function more than once and you should handle it. Pay attention that calling pthread_join twice from the same process has undefined behavior and you must avoid that.

3) getJobState – this function gets a JobHandle and updates the state of the job into the given JobState struct.

```
void getJobState(JobHandle job, JobState* state)
```

4) closeJobHandle – Releasing all resources of a job. You should prevent releasing resources before the job finished. After this function is called the job handle will be invalid.

```
void closeJobHandle(JobHandle job)
```

In case that the function is called and the job is not finished yet wait until the job is finished to close it.

In order to release mutexes and semaphores (pthread_mutex, sem_t) you should use the functions pthread_mutex_destroy, sem_destroy.

5) emit2 – This function produces a (K2*, V2*) pair. It has the following signature:

```
void emit2 (K2* key, V2* value, void* context)
```

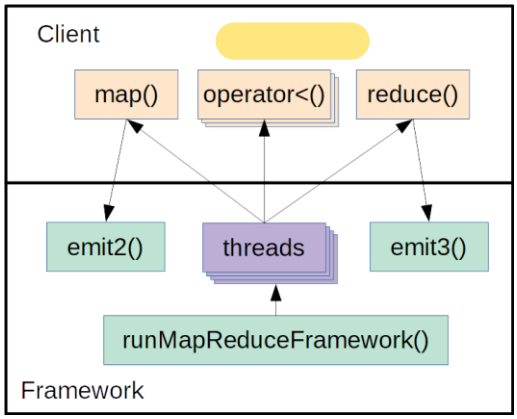
The function receives as input intermediary element (K2, V2) and context which contains data structure of the thread that created the intermediary element. The function saves the intermediary element in the context data structures. In addition, the function updates the number of intermediary elements using atomic counter.
Please pay attention that emit2 is called from the client's map function and the context is passed from the framework to the client's map function as parameter.

6) emit3 – This function produces a (K3*, V3*) pair. It has the following signature:

```
void emit3 (K3* key, V3* value, void* context)
```

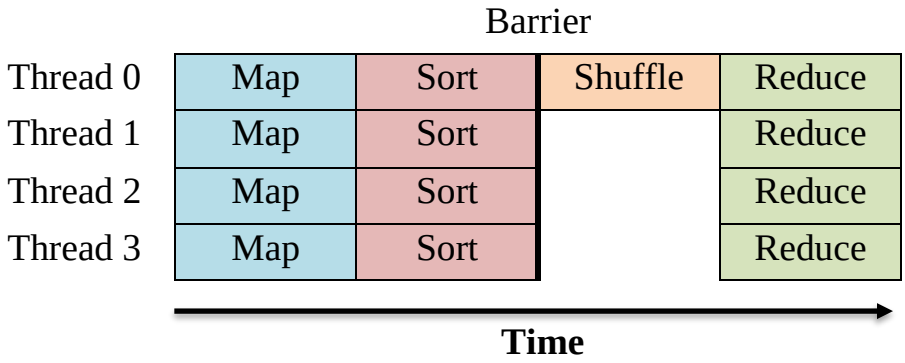
The function receives as input output element (K3, V3) and context which contains data structure of the thread that created the output element. The function saves the output element in the context data structures (output vector). In addition, the function updates the number of output elements using atomic counter.
Please pay attention that emit3 is called from the client's map function and the context is passed from the framework to the client's map function as parameter.

The following diagram contains a summary of the functions in the client and the framework. An arrow from function a to function b means that a calls b.



Framework Implementation Details

We will implement a variant of the MapReduce model according to the following diagram:



This diagram only shows 4 threads which is the case where the *multiThreadLevel* argument is 4.

In this design all threads except thread 0 run three phases: Map, Sort and Reduce, while thread 0 also runs a special shuffle phase between its Sort and Reduce phases.

In the general case (where *multiThreadLevel=n):*

- Thread 0 runs Map, Sort, Shuffle and then Reduce.
- Threads 1 through n-1 runs Map, Sort and then Reduce.

The only thread that can run the shuffle phase is thread 0.

Map Phase

In this phase each thread reads pairs of (*k1*, *v1*) from the input vector and calls the *map* function on each of them. The *map* function in turn will produce (*k2*, *v2*) and will call the *emit2* function to update the framework databases. We have two synchronisation challenges here:

1) Splitting the input values between the threads – this will be done using an atomic variable shared between the threads, an example of using an atomic variable in this manner is provided together with the exercise. Read it and run it before continuing.
The variable will be initialised to 0, then each thread will increment the variable and check its old value. The thread can safely call *map* on the pair in the index *old_value* knowing

that no other thread will do so. This is repeated until *old_value* is after the end of the input vector, as that means that all pairs have been processed and the Map phase has ended.

2) Prevent output race conditions – This will be done by separating the outputs. We will create a vector for each thread and then *emit2* will just append the new (*k2, v2)* pair into the calling thread's vector. Accessing the calling thread's vector can be done by using the *context* argument.

   - This solution will solve race condition between the different Map threads since every Map thread will work with a different vector.
   - The Shuffle thread will combine those vectors into a single data structure.

In the end of this phase, we have *multiThreadLevel* vectors of (*k2, v2*) pairs and all elements in the input vector were processed.

Sort Phase

Immediately after the Map phase each thread will sort its intermediate vector according to the keys within. Since every thread has its own vector, this phase needs no special synchronisation. std::sort can be used to implement this phase with relatively little code.

The Shuffle phase must only start after all threads finished their sort phases.

In the end of this phase, we must use a barrier – a synchronisation mechanism that makes sure no thread continues before all threads arrived at the barrier. Once all threads arrive, the waiting threads can continue. A sample C++ implementation of a barrier is provided together with the exercise, it is similar to the example in the presentation of Tutorial 4. You may use code from this example as is.

After the barrier, one of the threads will move on to the Shuffle phase while the rest will skip it and move directly to the Reduce phase.

Shuffle Phase

Recall that our goal in this phase is to create new sequences of (*k2, v2*) where in each sequence all keys are identical and all elements with a given key are in a single sequence.

Since our intermediary vectors are sorted, we know that all elements with the largest key must be at the back of each vector. Thus, creating the new sequence is simply a matter of popping these elements from the back of each vector and inserting them to a new vector. Now all elements with the second largest key are at the back of the vectors so we can repeat the process until the intermediary vectors are empty.

That is a task that is quite difficult to split efficiently into parallel threads, so we use a single Shuffle thread (thread 0) while all the other threads will wait until the shuffle phase will over. Whenever we finish creating a new vector for some identical key, we put it in a queue.

Use a vector for the queue (note that it is a vector of vectors), In addition use an atomic counter for counting the number of vectors in it. Whenever a new vector is inserted to the queue you should update the atomic counter.

Once all intermediary vectors are empty, the shuffling thread will move on to the Reduce phase.

You are encouraged to use semaphore at this phase to make all the threads to wait until the shuffle thread is complete. You can create semaphore using the function sem_init.

Reduce Phase

The reducing threads will wait for the shuffled vectors to be created by the shuffling thread. Once they wake up, they can pop a vector from the back of the queue and run *reduce* on it (Remember to lock the mutex when necessary).

The *reduce* function in turn will produce (*k3*, *v3*) pairs and will call *emit3* to add them to the framework data structures. These can be inserted directly to the output vector (*outputVec* argument of *startMapReduceJob*) under the protection of a mutex. The *emit3* function can access the output vector through its *context* argument.

General Remarks

1. Inside *MapReduceFramework.cpp* you are encouraged to define *JobContext* – a srtuct which includes all the parameters which are relevant to the job (e.g., the threads, state, mutexes…). The pointer to this struct can be casted to JobHandle. You are encouraged to use C++ static casting.
2. In order to check and update the job state, you **may** use atomic variables which are shared with running threads. Note that accessing multiple atomic variables is not atomic – take this under consideration or try implement them using a single 64bit atomic variable. There are 4 different stages (UNDEFINED, MAP, SHUFFLE, REDUCE), keep 2 bits to flag the stage, then you need to store the number of already processed keys and number of total keys to process (to calculate the task progress), use 31-bits for each number.
3. When a system call or standard library function fails (such as pthread_create or std::atomic load) you should print a single line in the following format:
"system error: text\n", text is a description of the error, and then exit(1).
4. You can assume that for each framework job the function closeJobHandle will be called.
5. The job state progress percentage is defined as the percentage of (key, value) pairs processed so far, out of all the (key, value) pairs that need to be processed in the current stage. In the map stage the percentage is the number of input vector items processed out of all the input vector items (input vector size). In the shuffle stage the percentage is the number of intermediate pairs shuffled out of all the intermediate pairs. In the reduce stage the percentage is the number of shuffled pairs (key, value) reduced out of all the shuffled pairs.

Your Assignment

Implement the functions of the framework (those that appear in the MapReduceFramework.h) according to the details above and compile them into a static library libMapReduceFramework.a
Do not change the header files.

You must use the pthread library, for creating threads, mutexes etc. as was taught in class. It is forbidden to use c++'s threads, mutexes, etc. You are also not allowed to use pipes, user level threads or forks. The only exception to this rule is using std::atomic.

Your code must be Thread-safe, startMapReduceJob must work correctly when called from two different threads simultaneously. Think what implications this has on your design.

Pay attention to your runtime and complexity, this exercise is all about performance, you should still avoid unnecessary copying of data or other preventable performance pains.
You must have no memory leaks.
The code you submit must not contain a main function and should not print anything.

Tips

- Go through all the resources provided before you write code and make sure you understand them. It will save you time.
- Since the keys only have the < operator and not ==, you can check if two keys a,b are identical by checking whether both a < b and b < a are false.
- Test early, test often: Using the example client make sure the each phase work correctly before heading to the next phase.
- The sample client is not enough. Make more complicated clients and test with them.
- You can use sleep and usleep to "recommend" certain scheduling (for example use sleep before starting the shuffle to simulate a situation where shuffle is getting CPU time first).

Submission

Submit a tar file containing the following:

- README file - The README should be structured according to the course guidelines. In order to be compliant with the guidelines, please use the README template that we provided.
- The source files for your implementation of the library.
- Makefile - Running *make* with no arguments should generate the *libMapReduceFramework.a* library.

You **don't** have to submit MapReduceClient.h and MapReduceFramework.h.

Late submission policy						
Submission time	**10.6, 23:55**	**13.6, 23:55**	**14.6, 23:55**	**15.6, 23:55**	**16.6, 23:55**	**17.6**
Penalty	0	-3	-10	-25	-40	-100