CPSC 457 - Assignment 4

Due date is posted on D2L.
Individual assignment. Group work is NOT allowed.
Weight: 22% of the final grade.

There are two programming questions in this assignment, both single-threaded. Question 1 should be quite straightforward to implement. Question 2 will require significant effort.

Q1 – Deadlock Detector (50 marks)

For this question you will write a C++ function `detect_deadlock()` that detects a deadlock in a simulated system with a single instance per resource type. The system state will be provided to this function as an ordered sequence of request and assignment edges. Your function will start by initializing an empty system state. Then, for each edge in the list, your function will update the system state for the edge and run a deadlock detection algorithm. Your function will return either as soon as it processes an edge that introduces a deadlock, or after all edges are inserted and no deadlock is detected. The signature of the function you need to implement is:

```
struct Result {
    int edge_index;
    std::vector<std::string> cycle;
};
Result detect_deadlock(const std::vector<std::string> & edges);
```

where `edges[]` is an ordered list of strings, each representing an edge. The function returns an instance of `Result` containing two fields as described below.

Your function will start with an empty system state – by initializing an empty graph data structure. For each string in `edges[]` it will parse it to determine if it represents an assignment edge or request edge, and update the graph accordingly. After inserting each edge, the function will run an algorithm that will look for a deadlock (cycle in the graph). If deadlock is detected, your function will stop processing any more edges and immediately return `Result`:

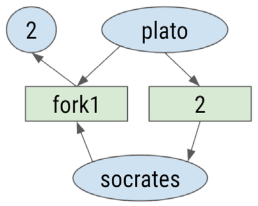
- with `edge_index` set to the index of the edge in `edges[]` that caused the deadlock; and
- with `cycle[]` containing process names that are involved in a deadlock. Order is arbitrary.

If no deadlock is detected after processing all edges, your function will indicate this by returning `Result` with `edge_index=-1` and an empty `cycle[]`.

Edge description

Your function will be given the edges as a vector of strings, where each edge will represent and edge. A request edge will have the format `"(P) -> (R)"`, and assignment edge will be of the form `"(P) <- (R)"`, where `(P)` and `(R)` are the names of the process and resource, respectively. Here is a sample input, and its graphical representation:

```
edges =
  [ "   2     <- fork1",
    " plato   -> fork1",
    " plato   ->   2  ",
    "socrates -> fork1",
    "socrates <-   2  "
  ]
```



The input above represents a system with three processes: `"plato"`, `"socrates"` and `"2"`, and two resources: `"fork1"` and `"2"`. The first line `"2 <- fork1"` represents an assignment edge, and it denotes process `"2"` currently holding resource `"fork1"`. The second line `"plato -> fork1"` is a request edge, meaning that process `"plato"` is waiting for resource `"fork1"`. The resource allocation graph on the right is a graphical representation of the input. Process and resource names are independent from each other, and it is therefore possible for processes and resources to have the same names.

Notice that each individual string may contain arbitrary number of spaces. Feel free to use the provided `simplify()` and `split()` functions from `common.cpp` to help you parse these strings.

Skeleton code

Start by downloading the following skeleton code:

```
$ git pull https://gitlab.com/cpsc457/public/deadlock-detect
$ cd deadlock-detect
$ make
```

You need to implement `detect_deadlock()` function my modifying `deadlock_detector.cpp`. The rest of the skeleton code contains a driver code (`main.cpp`) and some convenience functions you may use in your implementation (`common.cpp`). Only modify file `deadlock_detector.cpp`, and **do not** modify any other files.

If given no command line arguments, the driver code will read edge descriptions from standard input. It parses them into an array of strings, then calls your `detect_deadlock()`, and prints out results. The driver will ensure that the input passed to your function is syntactically valid, i.e. every string in `edges[]` will contain a valid edge. Here is how you run it on file `test1.txt`:

```
$ ./deadlock < test1.txt
Reading in lines from stdin...
Running detect_deadlock()...

edge_index : 6
cycle      : [12,7,7]
real time  : 0.0000s
```

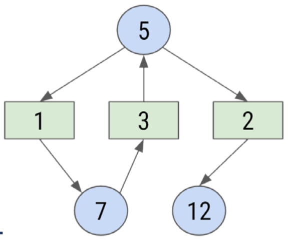
```
$ ./deadlock < test1.txt
Reading in lines from stdin...
Running detect_deadlock()...

edge_index : -1
cycle      : []
real time  : 0.0001s
```

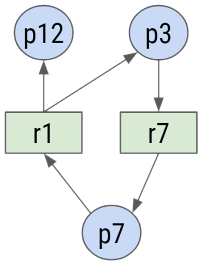
Please note that the above output on the left is incorrect because the skeleton code has an incomplete implementation of the deadlock detector that returns hard-coded values. Once implemented correctly, the output of the program will look like the one on the right. The correct output indicates no deadlock because there is no loop in the graph.

Few more examples:

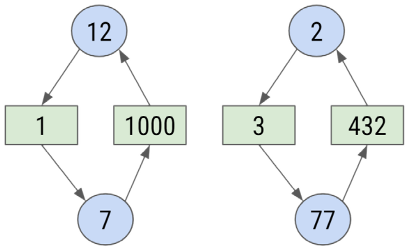
```
$ cat test2.txt
5 -> 1
5 <- 3
5 -> 2
7 <- 1
12 <- 2
7 -> 3
$ ./deadlock < test2.txt
edge_index : 5
cycle      : [5,7]
```



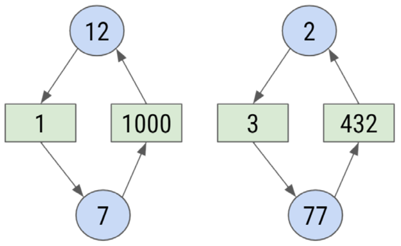
```
$ cat test3.txt
p7 <- r7
p7 -> r1
p3 -> r7
p3 <- r1
p12 <- r1
$ ./deadlock < test3.txt
edge_index : 3
cycle      : [p7,p3]
```



```
$ cat test4.txt
12 -> 1
12 <- 1000
7 -> 1000
7 <- 1
2 -> 3
2 <- 432
77 -> 432
77 <- 3
$ ./deadlock < test4.txt
edge_index : 3
cycle      : [12,7]
```



```
$ cat test5.txt
12 -> 1
12 <- 1000
7 -> 1000
2 -> 3
2 <- 432
77 -> 432
77 <- 3
7 <- 1
$ ./deadlock < test5.txt
edge_index : 6
cycle      : [2,77]
```



Limits

You may assume the following limits on input:

- Both process and resource names will contain at most 40 alphanumeric characters (digits, upper- and lower-case letters).
- Number of edges will be in the range [0 ... 30000].

Your solution should be efficient enough to run on any input within the above limits in less than 10 seconds. It is your job to design your own test cases. Hint: you should implement an efficient cycle-detection algorithm.

Marking

Your submission will be marked both on correctness and speed for a number of different test files. To get full marks, your program will need to finish in under 10 seconds on all cases. 90% of the marks will be based on tests with less than 10000 edges, which should be easy to achieve. For example, your program should be able to finish `test6.txt` under 10s on `linuxlab` machines.

The remaining 10% will be awarded only to submissions that can finish under 10s for ~30000 edges, which is significantly more difficult. You can test your code on the large `test7.txt` file to see if it is fast enough to get full marks.

Q2 – Scheduler simulation (50 marks)

For this question you will implement a round-robin CPU scheduling simulator for a given list of processes and a time slice. Each process will be described by an id, arrival time and CPU burst. Your simulator will run RR scheduling on these processes and for each process it will calculate its start time and finish time. Your simulator will also compute a condensed execution sequence of all processes. You will implement your simulator as a function `simulate_rr()` with the following signature:

```
void simulate_rr(
    int64_t quantum,
    int64_t max_seq_len,
    std::vector<Process> & processes,
    std::vector<int> & seq);
```

The input parameter `quantum` will contain a positive integer describing the length of the time slice and `max_seq_len` will contain the maximum length of execution order to be reported. The array `processes` will contain the description of processes, where struct `Process` is defined in `scheduler.h` as:

```
struct Process {
    int id;
    int64_t arrival_time, burst;
    int64_t start_time, finish_time;
};
```

The fields `id`, `arrival_time` and `burst` are the inputs to your simulator. Do not modify these.

You must populate the `start_time` and `finish_time` for each process with computed values. You must also report the condensed execution sequence of the processes via the output parameter `seq[]`. You need to make sure the reported order contains at most the first `max_seq_len` entries. The entries in `seq[]` will contain either a process ids, or `-1` to denote idle CPU.

Skeleton code

Download the skeleton code and compile it:

```
$ git pull https://gitlab.com/cpsc457/public/scheduler.git
$ cd scheduler
$ make
```

You need to implement `simulate_rr()` inside `scheduler.cpp`. The rest of the skeleton code contains a driver code (main.cpp) and some convenience functions you may use in your implementation (common.cpp). Only modify file `scheduler.cpp`, and do not modify any other files.

Using the driver on external files

The skeleton code provides a driver that parses command lines arguments to obtain the time slice and the maximum execution sequence length. It then parses standard input for the description of processes. The processes must be supplied to the driver by specifying each process on a separate line. Each line contains 2 integers: the first one denotes the arrival time of the process, and the second one the CPU burst length. For example:

```
$ cat test1.txt
```

```
1 10
3 5
5 3
```

This file contains information about 3 processes: P0, P1 and P2. The 2nd line "3 5" means that process P1 arrives at time 3 and it has a CPU burst of 5 seconds.

Once the driver parses the command line and standard input, it calls your simulator, and then prints out the results. For example, to run your simulator with `quantum=3` and `max_seq_len=20` on a file `test1.txt`, you would:

```
$ ./scheduler 3 20 < test1.txt
Reading in lines from stdin...
Running simulate_rr(q=3,maxs=20,procs=[3])
Elapsed time  : 0.0000s

seq = [0,1,2,]
+------------------------+-------------------+-------------------+-------------------+
| Id |            Arrival |             Burst |             Start |            Finish |
+------------------------+-------------------+-------------------+-------------------+
|  0 |                  1 |                10 |                 1 |                11 |
|  1 |                  3 |                 5 |                 3 |                 8 |
|  2 |                  5 |                 3 |                 5 |                 8 |
+------------------------+-------------------+-------------------+-------------------+
```

Please note that the outputs above are incorrect, as the skeleton contains an incomplete implementation of the scheduling algorithm. The correct results would look like this:

```
seq = [-1,0,1,0,2,1,0]
+------------------------+-------------------+-------------------+-------------------+
| Id |            Arrival |             Burst |             Start |            Finish |
+------------------------+-------------------+-------------------+-------------------+
|  0 |                  1 |                10 |                 1 |                19 |
|  1 |                  3 |                 5 |                 4 |                15 |
|  2 |                  5 |                 3 |                10 |                13 |
+------------------------+-------------------+-------------------+-------------------+
```

IMPORTANT: If your simulation detects that an existing process exceeds its time slice at the same time as a new process arrives, you need to insert the existing process into the ready queue before inserting the newly arriving process.

Limits

You may make the following assumptions about the configuration file:

- The processes are sorted by their arrival time, in ascending order. Processes arriving at the same time should be inserted into the ready queue in the order they are listed.
- Process IDs will be consecutively numbered starting with 0.
- All processes are 100% CPU-bound, i.e., a process will never be in the WAITING state.
- There will be between 0 and 30 processes.
- Time slice and CPU bursts will be integers in the range [1 … 2^{62}]
- Process arrival times will be integers in the range [0 … 2^{62}]

The skeleton repository contains few test files and the `README.md` has some results. You should also design your own test data to make sure your program works correctly and efficiently for all of the above limits.

Marking

Your submission will be marked both on correctness and speed for a number of different test files. To get full marks, your program will need to finish in under 10 seconds on all test cases. About half of the test cases will include inputs with small values for arrival times and CPU bursts. But there will be some test cases with very large arrival times, and/or CPU bursts, and very small time-slices.

Hints

Start with a simulation loop that increments current time by 1. This should make your simulator work fast enough for small arrival times and bursts. Once you are convinced that it works correctly, you can try to improve it to run fast for large burst and arrival numbers. To do this, you will need to determine the optimal value of the amount by which you increment the current time. I include some hints in the appendix on how this can be achieved.

Submission

Submit 2 files to D2L for this assignment. **Do not submit a ZIP file. Submit individual files.**

`deadlock_detector.cpp`	solution to Q1
`scheduler.cpp`	solution to Q2

Please note – you need to **submit all files every time** you make a submission, as the previous submission will be overwritten.

General information about all assignments

1. All assignments are due on the date listed on D2L. Late submissions will not be marked.
2. Extensions may be granted only by the course instructor.
3. After you submit your work to D2L, verify your submission by re-downloading it.
4. You can submit many times before the due date. D2L will simply overwrite previous submissions with newer ones. It is better to submit incomplete work for a chance of getting partial marks, than not to submit anything. Please bear in mind that you cannot re-submit a single file if you have already submitted other files. Your new submission would delete the previous files you submitted. So please keep a copy of all files you intend to submit and resubmit all of them every time.
5. Assignments will be marked by your TAs. If you have questions about assignment marking, contact your TA first. If you still have questions after you have talked to your TA, then you can contact your instructor.
6. All programs you submit must run on `linuxlab.cpsc.ucalgary.ca`. If your TA is unable to run your code on the Linux machines, you will receive 0 marks for the relevant question.
7. Unless specified otherwise, you must submit code that can finish on any valid input under 10s on linuxlab.cpsc.ucalgary.ca, when compiled with `-O2` optimization. Any code that runs longer than this may receive a deduction, and code that runs for too long (about 30s) will receive 0 marks.
8. **Assignments must reflect individual work**. Here are some examples of what you are not allowed to do for individual assignments: you are not allowed to copy code or written answers (in part, or in whole) from anyone else; you are not allowed to collaborate with anyone; you are not allowed to share your solutions (code or pseudocode) with anyone; you are not allowed to sell or purchase a solution; you are not allowed to make your code available publicly. This list is not exclusive. For further information on plagiarism, cheating and other academic misconduct, check the information at this link: http://www.ucalgary.ca/pubs/calendar/current/k-5.html.
9. We will use automated similarity detection software to check for plagiarism. Your submission will be compared to other students (current and previous), as well as to any known online sources. Any cases of detected plagiarism or any other academic misconduct will be investigated and reported.

Appendix 1 – hints for Q1

To get <10s run time on medium sized files such as `test6.txt`, I suggest you use the following data structures (or similar) to implement a graph:

```
class Graph {
    std::unordered_map<std::string, std::vector<std::string>> adj_list;
    std::unordered_map<std::string, int> out_counts;
    ...
} graph;
```

The field `adj_list` is a hash table of dynamic arrays, representing an adjacency list. Insert nodes into it so that `adj_list["node"]` will contain a list of all nodes with edges pointing towards "node". The `out_counts` field is a hash table of integers, representing the number of outgoing edges for every node. Populate it so that `out_counts["node"]` contains the number of edges pointing out from "node".

With these data structures you can implement a simple yet efficient topological sort (pseudo-code):

```
out = out_counts # copy out_counts so that we can modify it
zeros[] = find all nodes in graph with outdegree == 0
while zeros is not empty:
 n = remove one entry from zeros[]
 for every n2 of adj_list[n]:
   out[n2] --
   if out[n2] == 0:
     append n2 to zeros[]
cycle[] = all nodes n that represent a process and out[n]>0
```

To get <10s run time on big files such as `test7.txt`, you can use the same algorithm as above, but you will need to switch to even more efficient data structures. The problem with the hash tables is having to calculate hashes on strings, and then having to deal with collisions, multiple times as you run the topological sort. To avoid this, you can pre-convert all strings (process and resource names) into consecutive integers as you process edges, and then use fast dynamic arrays to store the adjacency list and outdegree counts:

```
class FastGraph {
    std::vector<std::vector<int>> adj_list;
    std::vector<int> out_counts;
    ...
} graph;
```

You can use the provided `Word2Int` class to help you with converting strings to unique consecutive integers. The topological sort algorithm will be the same as above. Do not forget to convert the integers back to strings at the end, to correctly populate `cycle[]`.

Appendix 2 – hints for Q2

Here are some basic optimizations:

- any time you start executing a job, and the job will finish before it exceeds the quantum, you can finish the job and advance time to the end time of the job. If any jobs arrive during this time, insert those into RQ.
- if you are executing last job (i.e., RQ is empty, and no more jobs arriving), then you can finish executing the current job, and end simulation.
- if RQ is empty and CPU is idle, then you can skip current time to the arrival of the next job.
- if RQ is empty but CPU has a job, then you can execute multiple time slices as long as you don't increment current time past next arrival time.

The hardest part is to optimize the case when CPU is idle, but RQ is not empty, and there are jobs still arriving in the future. This is especially needed when the time slice is tiny but arrival times and/or burst times are very large. Here are some hints for an optimization that you can do after you have already populated the execution sequence, and after every job in RQ has a recorded start time:

- ask yourself this question: could you execute one quantum for every job in RQ without any jobs finishing, and without going past the arrival time of the next job? If you could, that would not change the order of jobs in the RQ, and you would not miss the end time for any jobs, and you would not miss arrival time for any job. In other words, you could increment current time by `rq.size()*quantum` without changing the state of the system, as long as you update the remaining time for each job in the RQ by subtracting quantum.

- next question is: how many times could you do the above? i.e. what is the maximum safe `N` such that you can increment current time by `N*rq.size()*quantum`? The `N` needs to be as big as possible, but small enough that no jobs will finish during this time, and no jobs will arrive during this time.