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1DV512 - Operating System
Individual Assignment 2

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1. Introduction

CPU scheduling plays an important role for operating system. By implementing different strategies, the performance of the waiting time of each process may vary differently [1]. From non-preemptive First-Come, First-Served (FCFS) scheduling strategy to preemptive Round Robin (RR) scheduling method, the industrial experts spare no effort to improve computing performance and reduce the average waiting time [1]. In this assignment, two modern schedulers–FreeBSD ULE and Linux CFS will be examined in detail.

First of all, eight questions regarding a comparison of FreeBSD ULE and Linux CFS schedulers will be answered and discussed. Furthermore, a Java-based programming task in terms of scheduling algorithm will be implemented which will simulate the execution of processes and present its performance.

2. Task 1

In this section, the research report Bouron et al. (2018) will be discussed [2]. The aim of this part is to present a deeper understanding of the differences in the scheduling algorithms between FreeBSD's ULE and Linux's CFS.

2.1 Does ULE support threads, or does it support processes only? How about CFS?

According to Bouron et al., ULE and CFS are both designed to schedule large numbers of threads on multicore machines [2]. However, when comparing the both designs, ULE is considered a simpler scheduler in terms of the amounts of code and applied algorithm, while CFS implements more complicated strategy and algorithm [2].

2.2 How does CFS select the next task to be executed?

Compared to FreeBSD ULE (2950 lines of code), the scheduler of Linux CFS is more complex with a total of 17900 lines of code in the latest LTS Linux kernel [2]. Compared to FreeBSD's FIFO algorithm, Linux's CFS utilized a different strategy to run next task. In CFS, a core decides which thread to run next based on prior execution time, priority, and perceived cache behavior of the threads in its runqueue [2]. Instead of evening out the number of threads between cores in ULE, CFS aims to even out the average amount of pending work.

2.3 What is a cgroup and how is it used by CFS? Does ULE support cgroups?

The notion of fairness in Linux CFS has a series of changes and updates [2]. Before Linux 2.6.38, the fairness was between threads which has been changed to between applications after 2.6.38 [2]. Before 2.6.38, every thread is treated as separated entity and distributed with same share resources as other threads in the system, therefore an application that used more threads will occupy more system resources than single-threaded applications [2]. This design, however, is changed in the more recent kernel. In the new design, threads of the same application are grouped into a structure called cgroup [2]. A cgroup has a vruntime that corresponds to the sum of the vruntimes of all of its threads [2]. CFS will then utilize its algorithm on cgroup to ensure the fairness between groups of threads [2]. When a cgroup is chosen to be scheduled, the thread with the lowest vruntime will be executed to make sure the fairness within the group [2]. Furthermore, cgroup can also be nested which means that, for example, system can firstly configure the fairness among different users then fairness between the applications of a given user [2]. By comparison, ULE does not use cgroups in its scheduling implementation. In ULE, two runqueues are used to schedule threads that is different from cgroup strategy [2].

2.4 How many queues in total does ULE use? What is the purpose of each queue?

In ULE, three different queues are used for scheduling [2]:

- The first queue is used to contain interactive threads
- The second queue is used to contains batch threads
- The third queue is used to contains the idle task

The goal of having two runqueues is to give priority to interactive threads [2]. According to this design, batch processes usually execute without user interaction, and thus scheduling latency is less important [2]. Moreover, ULE keeps track of the interactivity of a thread using an interactivity penalty metric between 0 and 100 [2]. In this manner, ULE balances the interactive and batch runqueues.

2.5 How does ULE compute priority for various tasks?

In ULE, two runqueues – interactive threads and batch threads are used to create priority for tasks. This is because in ULE's design, it tends to give interactive threads priority due to batch threads normally run without user interaction [2]. ULE will keep track of a thread and measure it with interactivity penalty metric between 0 and 100. By using the penalty function, ULE will better compute "interactivity penalty + niceness" [2]. First, a thread's interactive score lower than 30 will be considered as interactive [2]. Second a negative score of nice value will also contribute to an obvious interactive thread [2]. The above algorithm will benefit ULE to compute priority for different tasks.

Moreover, inside the interactive and batch runqueues, threads are further sorted by priority. For interactive threads, the priority is identified by a linear interpolation of their score (0 has highest interactive priority and 30 has lowest) [2]. Inside the interactive runqueue, there is one FIFO per priority [2]. For batch threads, the longer runtime the thread has, the lower priority it will be [2]. The niceness of a thread will be considered to get a linear effect on priority [2]. Batch runqueue also is also designed with FIFO per priority [2].

2.6 Do CFS and ULE support task preemption? Are there any limitations?

In ULE, full preemption is disabled which means that only kernel threads can preempt others [2]. By comparison, CFS tends to preempt the running thread when the thread has just been woken up and which owns a vruntime much smaller than the vruntime of the currently executing thread (in practice this difference is around 1 ms) [2]. Implementing preemption means that the scheduler will be equipped with more complex algorithm, and it normally has longer code [2]. In the experiment, though CFS balances the load much faster, CFS never realizes perfect load balance [2]. As mentioned in this research, "CFS only balances the load between NUMA nodes when the imbalance between the two nodes is "big enough" (25% load difference in practice)". In the end, some cores will handle more threads than others [2]. However, this disadvantage of CFS may convert to merit when the it faces a large amount of imbalance loads in the system.

2.7 Did Bouron et al. discover large differences in per-core scheduling performance between CFS and ULE? Which definition of "performance" did they use in their benchmark, and why?

In the per-core scheduling performance experiment, Bouron et al. analysed 37 applications in terms of database workload and NAS applications [2]. Overall, the scheduler has little influence on most workload [2]. According to the test, most applications used threads that all perform same work, therefore, both CFS and ULE perform scheduling all of the threads in a round-robin manner. The data shows that the average performance differences is 1.5% which ULE is slightly better than CFS [2].

They define "performance" as: for database workloads and NAS applications, the performance can be compared by the number of operations per second; for the other applications the performance is compared by "1/execution time" [2]. The higher the "performance", the better a scheduler performs [2]. This design is due to the different nature of applications in the real world. For database type software, the ability of high concurrency is usually considered. By comparison, execution time is a good index to identify its performance.

2.8 What is the difference between the multi-core load balancing strategies used by CFS and ULE? Is any of them faster? Does any of them typically reach perfect load balancing?

In multi-core load balancing experiment, the research result shows that the multi-core load balancing strategies are different between ULE and CFS. In a multicore setting, CFS relies on a more complex load metric which applies a hierarchical load balancing strategy that runs every 4ms that intends to even out the amount of work on all cores of the machine [2]. This, however, is different from evening out the number of threads. In ULE, as soon as the threads are unpinned, idle cores will steal threads (at most one per core) from core 0, thus right after the unpinning, core 0 has 512−31 = 481 threads while every other core has 1 thread [2]. Since the load balancer only migrates one thread at a time from core 0, it demands more than 450 load balancer invocations or around 240 seconds to reach a balanced state [2]. By comparison, 0.2 seconds after the unpinning, CFS has migrated more that 380 threads from core 0, therefore CFS balances the load much faster [2].

Though ULE could spend longer time, the research result shows that ULE has better performance in terms of reaching perfect load balancing. Worth noting that CFS can never achieve perfect balance in the research [2]. CFS can only balance the load between NUMA nodes when the imbalance between the two nodes is about 25% load difference in practice which leads to that cores in one node can have 18 threads while cores in another only have 15 [2]. The average performance difference between CFS and ULE is not obvious, only 2.75% in favor of ULE. In the performance analysis part, we can find that different applications may perform differently regarding using CFS and ULE which means CFS and ULE having its own pros and cons.

Over time, the periodic load balancer is triggered and tries to balance the thread count. if user has 11 threads, one is CPU-intensive thread and others are mostly sleep, then CFS will schedule the 10 sleep threads on a single core [2]. ULE, on the other hand, tends to even out the number of threads per core. In ULE, the load of a core is simply defined as the number of threads currently runnable on this core. ULE does not group threads into cgroup but rather considers each thread as a separate entity.

3. Task 2

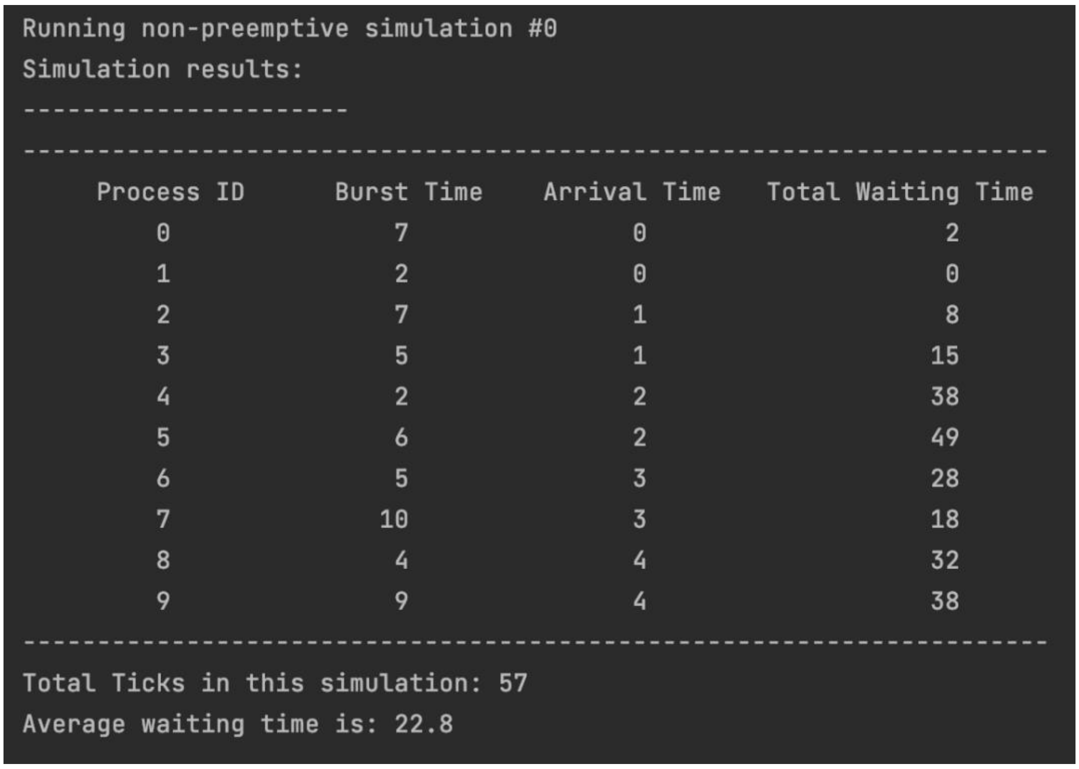
In this section, the experiments regarding the implementation of the random scheduling algorithm based on Java programming language will be presented [2]. The aim of this part is to explore the features of the random scheduler for CPU with respects to non-preemptive and preemptive algorithms.

3.1 Implementation of the scheduling algorithm

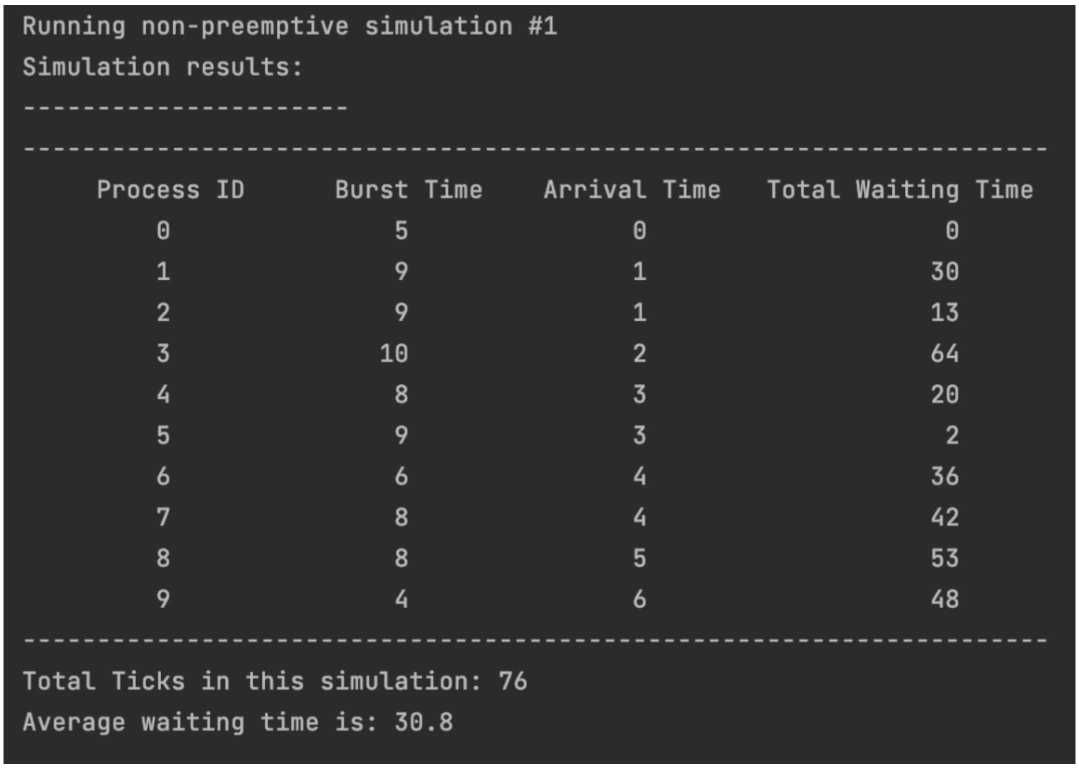
See source code in the uploaded package.

3.2 Simulation results

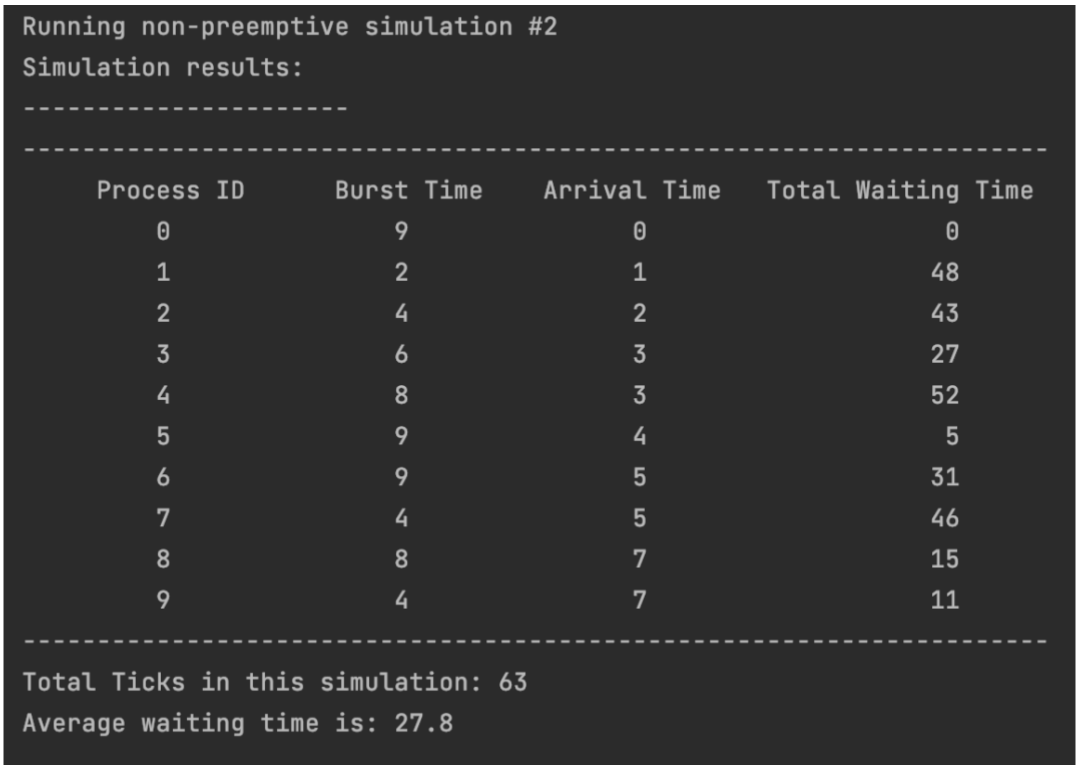
3.2.1 Non-preemptive version



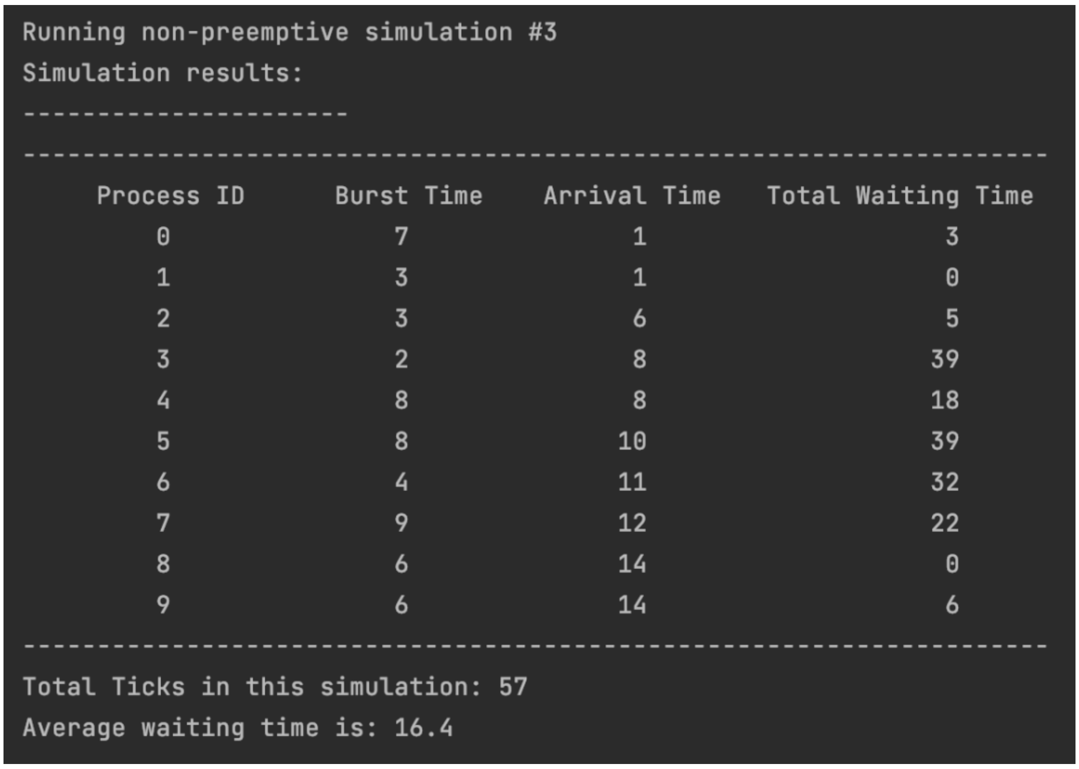
```
Running non-preemptive simulation #0
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               7              0                 2
         1               2              0                 0
         2               7              1                 8
         3               5              1                15
         4               2              2                38
         5               6              2                49
         6               5              3                28
         7              10              3                18
         8               4              4                32
         9               9              4                38
--------------------------------------------------------------------
Total Ticks in this simulation: 57
Average waiting time is: 22.8
```



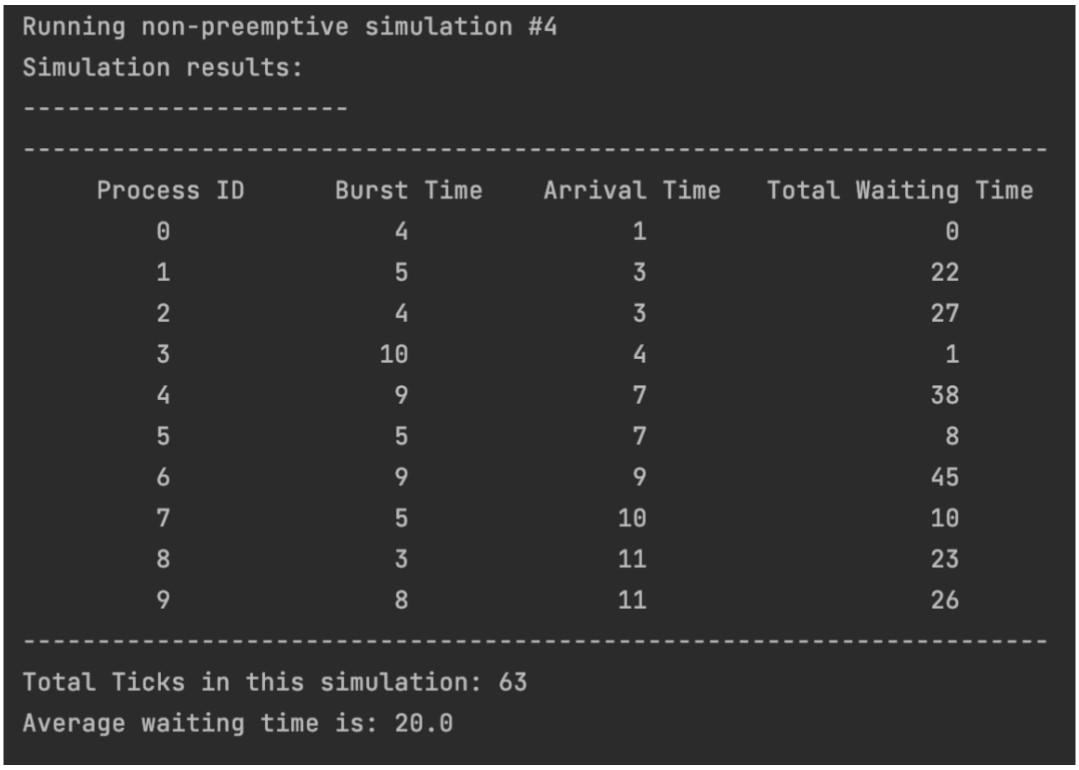
```
Running non-preemptive simulation #1
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               5              0                 0
         1               9              1                30
         2               9              1                13
         3              10              2                64
         4               8              3                20
         5               9              3                 2
         6               6              4                36
         7               8              4                42
         8               8              5                53
         9               4              6                48
--------------------------------------------------------------------
Total Ticks in this simulation: 76
Average waiting time is: 30.8
```



```
Running non-preemptive simulation #2
Simulation results:
----------------------
---------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               9              0                  0
         1               2              1                 48
         2               4              2                 43
         3               6              3                 27
         4               8              3                 52
         5               9              4                  5
         6               9              5                 31
         7               4              5                 46
         8               8              7                 15
         9               4              7                 11
---------------------------------------------------------------------
Total Ticks in this simulation: 63
Average waiting time is: 27.8
```

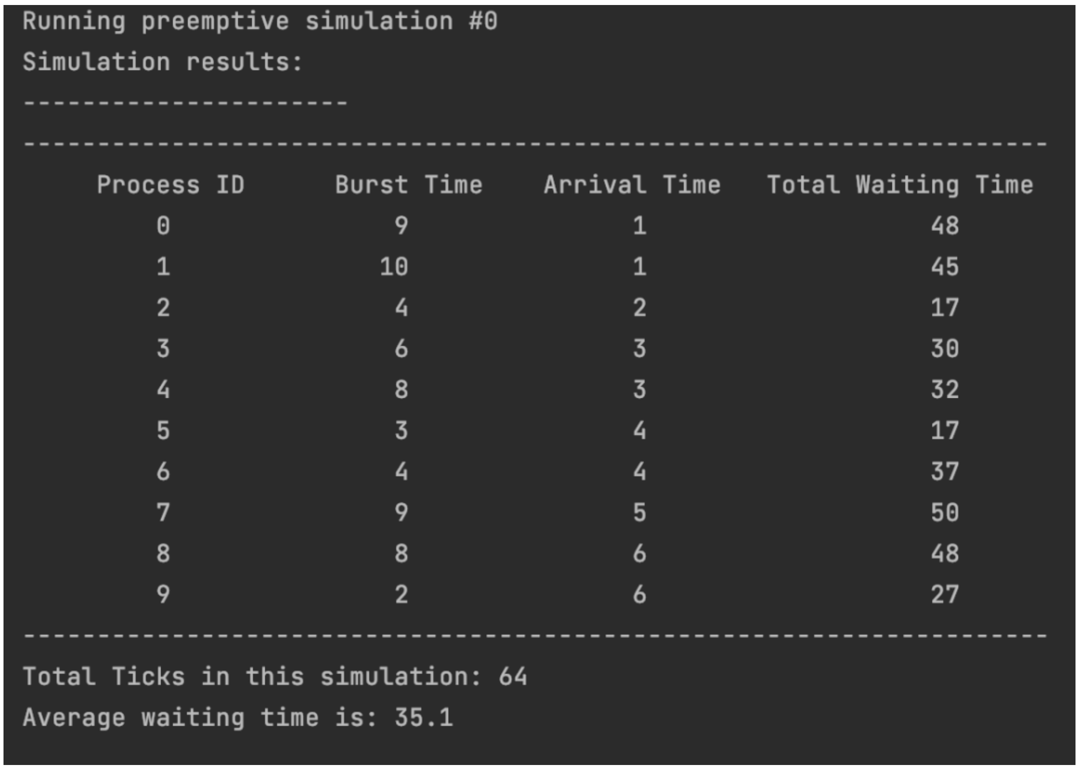


```
Running non-preemptive simulation #3
Simulation results:
----------------------
---------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               7              1                  3
         1               3              1                  0
         2               3              6                  5
         3               2              8                 39
         4               8              8                 18
         5               8             10                 39
         6               4             11                 32
         7               9             12                 22
         8               6             14                  0
         9               6             14                  6
---------------------------------------------------------------------
Total Ticks in this simulation: 57
Average waiting time is: 16.4
```

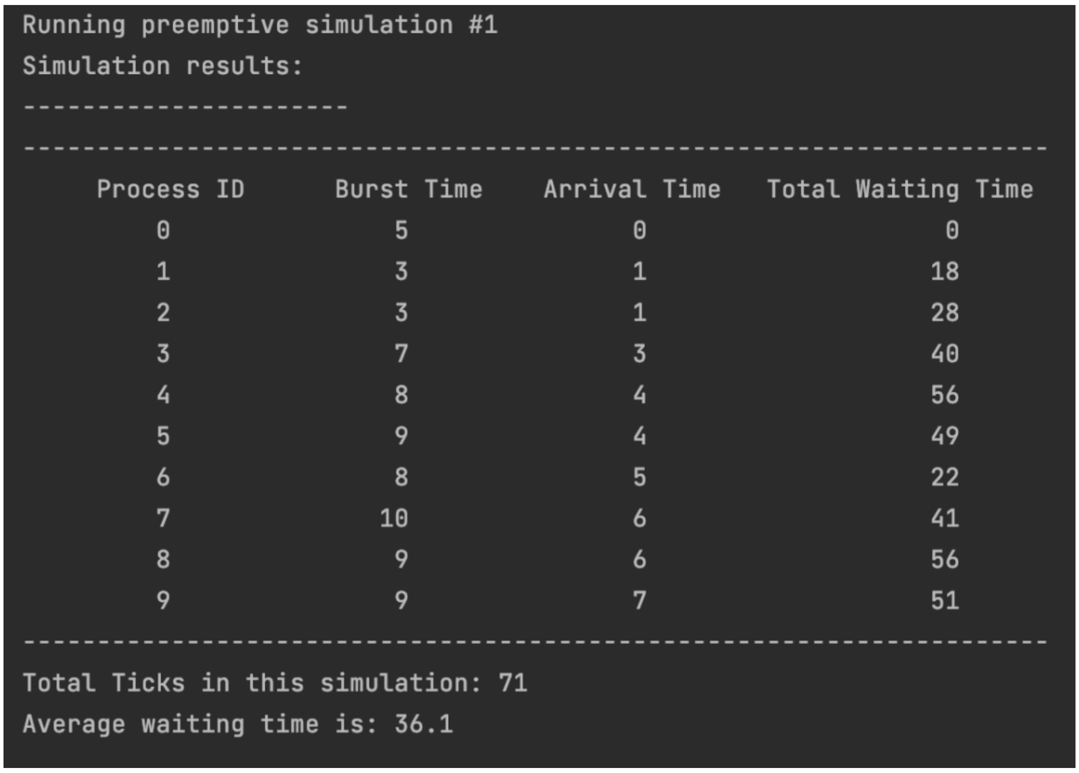


```
Running non-preemptive simulation #4
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               4               1                   0
         1               5               3                  22
         2               4               3                  27
         3              10               4                   1
         4               9               7                  38
         5               5               7                   8
         6               9               9                  45
         7               5              10                  10
         8               3              11                  23
         9               8              11                  26
--------------------------------------------------------------------
Total Ticks in this simulation: 63
Average waiting time is: 20.0
```

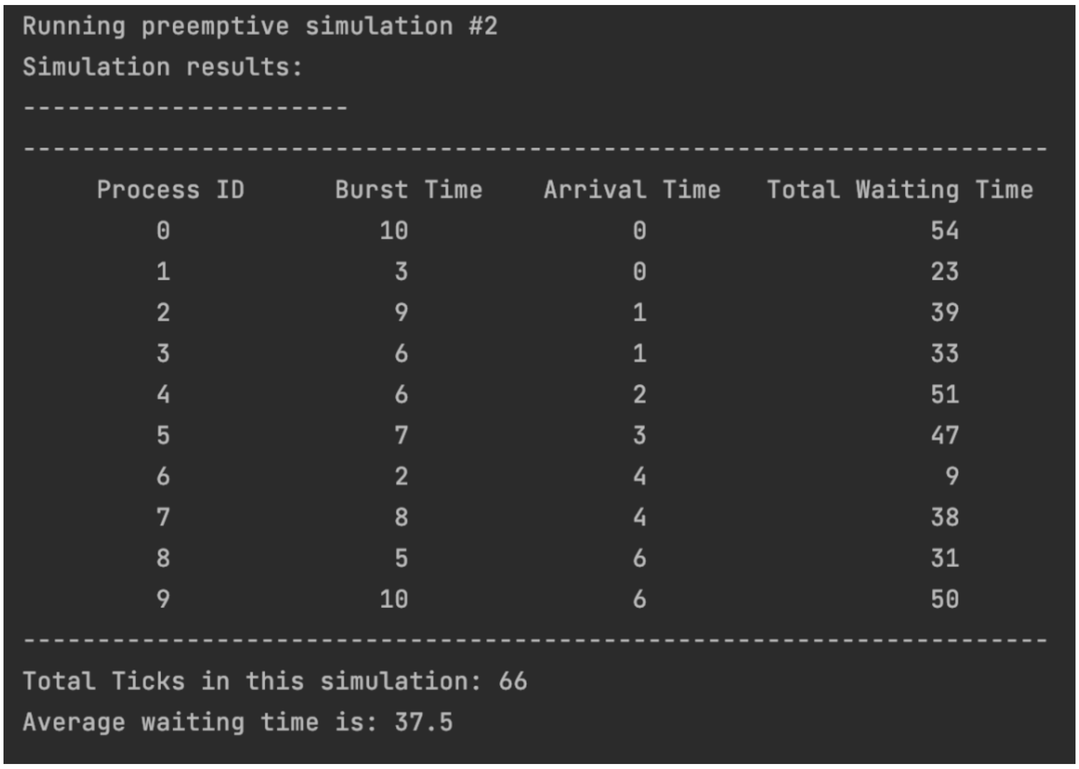
3.2.1 Preemptive version



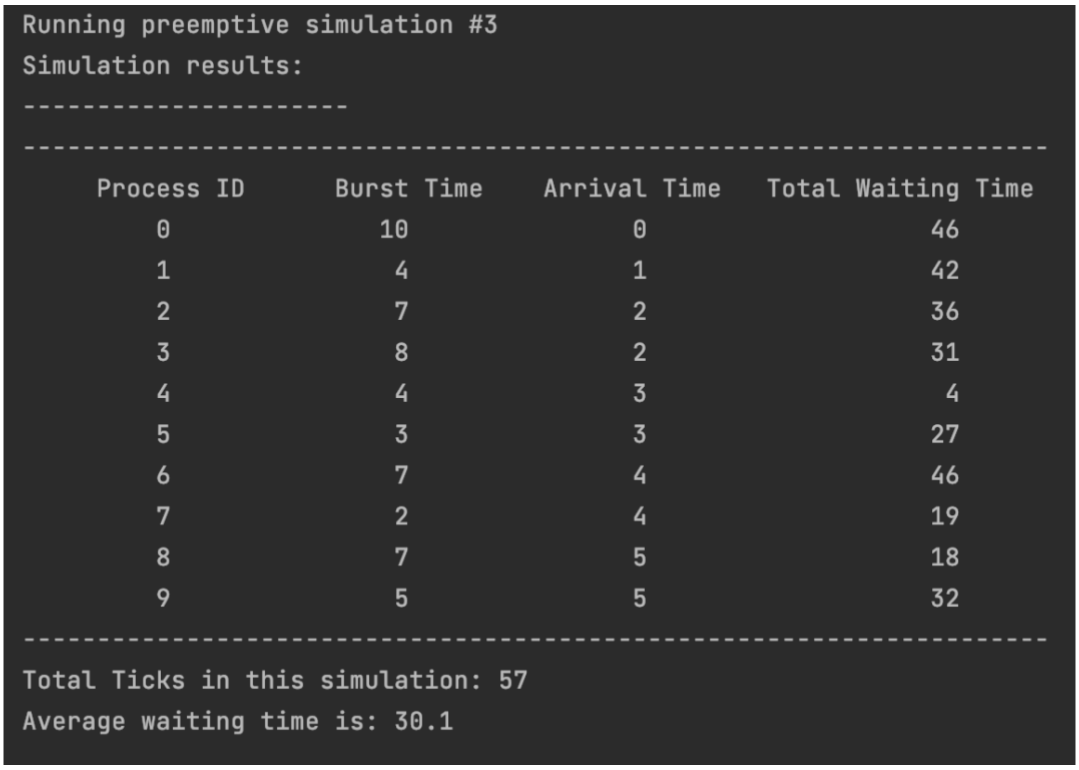
```
Running preemptive simulation #0
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               9               1                  48
         1              10               1                  45
         2               4               2                  17
         3               6               3                  30
         4               8               3                  32
         5               3               4                  17
         6               4               4                  37
         7               9               5                  50
         8               8               6                  48
         9               2               6                  27
--------------------------------------------------------------------
Total Ticks in this simulation: 64
Average waiting time is: 35.1
```



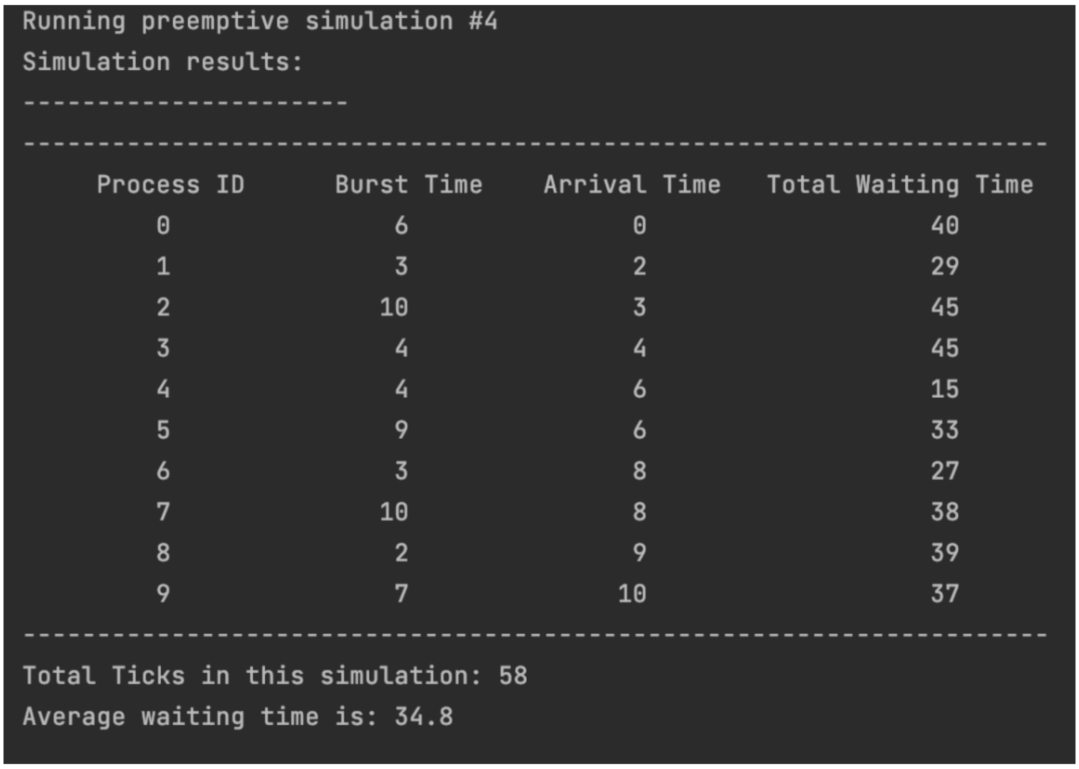
```
Running preemptive simulation #1
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               5              0                    0
         1               3              1                   18
         2               3              1                   28
         3               7              3                   40
         4               8              4                   56
         5               9              4                   49
         6               8              5                   22
         7              10              6                   41
         8               9              6                   56
         9               9              7                   51
--------------------------------------------------------------------
Total Ticks in this simulation: 71
Average waiting time is: 36.1
```



```
Running preemptive simulation #2
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              10              0                   54
         1               3              0                   23
         2               9              1                   39
         3               6              1                   33
         4               6              2                   51
         5               7              3                   47
         6               2              4                    9
         7               8              4                   38
         8               5              6                   31
         9              10              6                   50
--------------------------------------------------------------------
Total Ticks in this simulation: 66
Average waiting time is: 37.5
```



```
Running preemptive simulation #3
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               10             0                  46
         1                4             1                  42
         2                7             2                  36
         3                8             2                  31
         4                4             3                   4
         5                3             3                  27
         6                7             4                  46
         7                2             4                  19
         8                7             5                  18
         9                5             5                  32
--------------------------------------------------------------------
Total Ticks in this simulation: 57
Average waiting time is: 30.1
```



```
Running preemptive simulation #4
Simulation results:
----------------------
--------------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0                6             0                  40
         1                3             2                  29
         2               10             3                  45
         3                4             4                  45
         4                4             6                  15
         5                9             6                  33
         6                3             8                  27
         7               10             8                  38
         8                2             9                  39
         9                7            10                  37
--------------------------------------------------------------------
Total Ticks in this simulation: 58
Average waiting time is: 34.8
```

3.3 Discussion of the simulation results

3.3.1 Observable pattern of the simulations

In section 3.2, the simulation results of non-preemtive scheduler and preemtive scheduler are presented separately. In the non-preemtive scheduling experiment, the ticks of the simulations are 57, 76, 63, 57, 63 which lead to the average ticks with 63.2; the average waiting time of non-preemtive version are 22.8, 30.8, 27.8, 16.4, 20 suggesting that the average waiting time of five simulations is 23.56. By comparison, the average ticks and waiting time of the five simulations of preemtive scheduler are 63.2 and 34.72 respectively. According to the above findings, both the non-preemptive and preemptive scheduling algorithms have similar total ticks while the preemptive scheduler does have longer average waiting time compared to non-preemptive scheduler.

3.3.2 The influence of RNG seed and number of simulations

In this section, the experimental influence factors regarding RNG seed and number of the simulation will be investigated. In order to improve a better readability, only the experiment results will be presented in this section. The screenshots of the simulations can be found in Appendix.

3.3.2.1 The influence of RNG seed

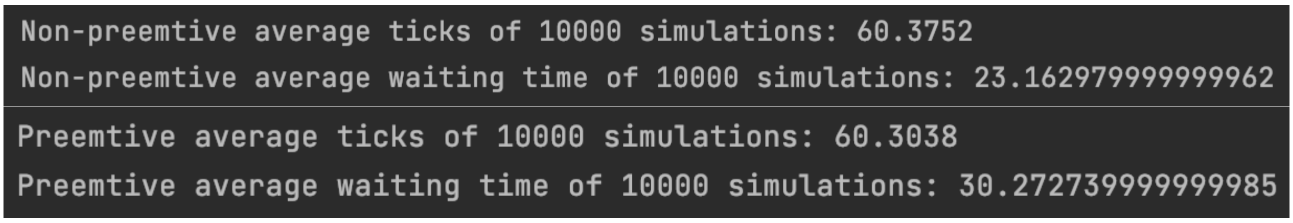
According to the control variable method, the simulation times will be controlled as five times in this experiment and random RNG seeds will be used for different tests. The RNG seeds are generated by “RandomSeedGenerator.class” in the uploaded source code package.

RNG seed	Non-preemtive average ticks	Preemtive average ticks	Non-preemtive average waiting time	Preemtive average waiting time
29550455	55.8	60.4	20.98	33.56
16590675	64	58.4	26.8	28.08
13929885	56.2	59	20.08	27.96

From this experiment, the observable pattern which is from 3.3.1 can be found again even the RNG seed has different values. The average waiting time of preemptive scheduler is longer than non-preemtive version no matter the value of RNG seed.

3.3.2.2 The influence of simulations times

In this experiment, the RNG seed value will be controlled as the author’s birthday, while the simulation times are set to 10000. The test results can be compared with the findings of 3.3.1. The research result can be found from the following screenshots:



```
Non-preemtive average ticks of 10000 simulations: 60.3752
Non-preemtive average waiting time of 10000 simulations: 23.162979999999962
```

```
Preemtive average ticks of 10000 simulations: 60.3038
Preemtive average waiting time of 10000 simulations: 30.272739999999985
```

Simulation Times	Non-preemtive average ticks	Preemtive average ticks	Non-preemtive average waiting time	Preemtive average waiting time
5	63.20	63.20	23.56	34.72
10000	60.38	60.30	23.16	30.27

The research results of 3.2.2.2 with 10000 simulations verified again the findings from 3.3.1 that the preemptive version of scheduler has longer average waiting time compared to the non-preemptive version while the average ticks of both versions are similar.

3.3.3 Comparison between the Random Scheduling and FCFS

The Random Scheduling and First Come and First Serve (FCFS) are different CPU scheduling algorithms. Each of them has its own pros and cons. FCFS, seeing the name and knowing the meaning, has the most obvious advantage that it is easy to implement compared to Random Scheduling strategy [3]. However, the limitations of FCFS are also very obvious which can be found in the following aspects. First of all, the processes with less execution time may have to wait more time due to the longer processes are in front of the short processes which will result in longer average waiting time and lower CPU and devices efficacy [3]. Furthermore, FCFS is not suitable for time-sharing systems i.e. each user needs to get a share of the CPU at regular interval [3]. Moreover, FCFS has its own order of preference i.e. it favors CPU bound process then I/O bound process [3].

By comparison, the Random Scheduling algorithm can solve the long waiting time by randomly picking the available scheduled processes, which can reduce waiting time and avoid continuously running processes with long burst time that will improve CPU and devices efficiency. The disadvantage of such algorithm is also very obvious that the implementation of such scheduler is normally more complicated than FCFS. More aspects such as CPU quantum time, preemptive strategy and non-preemptive strategy need to consider in the design.

4. Reflection

This assignment provides a valuable chance to systematically study the CPU algorithms from FreeBSD ULE and Linux CFS perspectives. Each CPU scheduling implementation have its advantages and disadvantages. From the structural design, the implementation of ULE is more lightweight compared to CFS algorithm which utilizes FIFO for runqueues and intends to even out the number of threads per core. The CFS, however, has more complex implementation and the run logic which strive to even out the average amount of pending work [2]. The analysis points out the performance differences between ULE and CFS are not obvious in general. Users can decide to use which scheduler depending on the actual business scenario. For example, when the computers need to face a large amount of imbalance loads in the system, the CFS algorithm can be the prior choice. By contrast, when system intends to reach a perfect balance among all threads, then the ULE will be an ideal option.

The implementation of scheduling algorithm is an interesting part of this assignment which helps to understand how does CPU schedule and handle processes in preemptive and non-preemptive manners. The research results suggest that the non-preemptive random scheduler has shorter average waiting time than preemptive version. In this research, control variable research method is used for exploring the influences of RNG seed and simulation numbers in order to provide a reliable analysis.

References

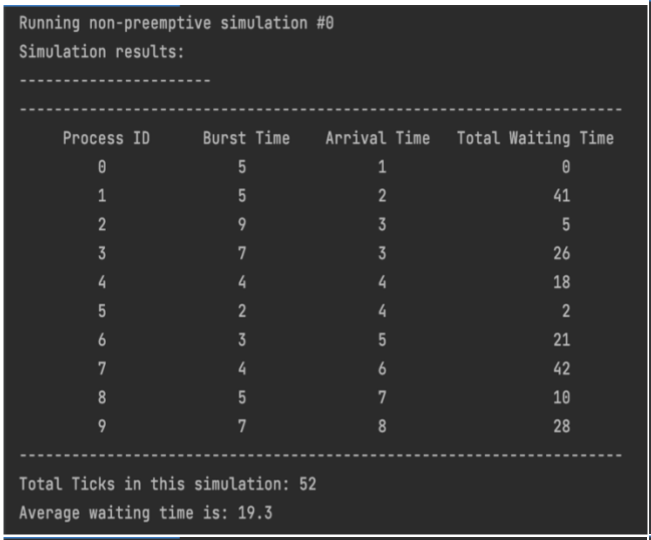
[1] Silberschatz A, Galvin P, Gagne G, Operating Systems Concepts (Tenth Edition), International Student Version, John Wiley & Sons, ISBN 978-1-118-06333-0.

[2] Bouron J, Chevalley S, Lepers B, Zwaenepoel W, EPFL, Gouicem R, Lawall J, Muller G, Sopena J, “*The Battle of the Schedulers: FreeBSD ULE vs. Linux CFS*”, ISBN 978-1-939133-02-1.

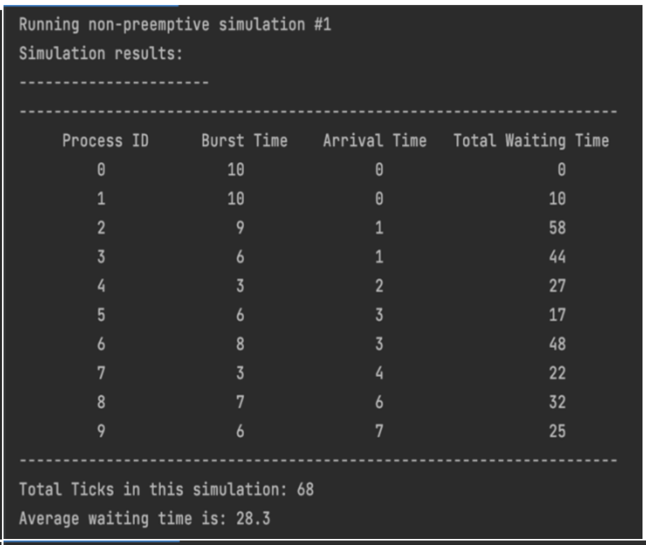
[3] Geeksforgeeks, “*Advantages and Disadvantages of various CPU scheduling algorithms*”, [2021-12-09], url: [https://www.geeksforgeeks.org/advantages-and-disadvantages-of-various-cpu-scheduling-algorithms/]

Appendix: Screenshots for section 3.3.2.1

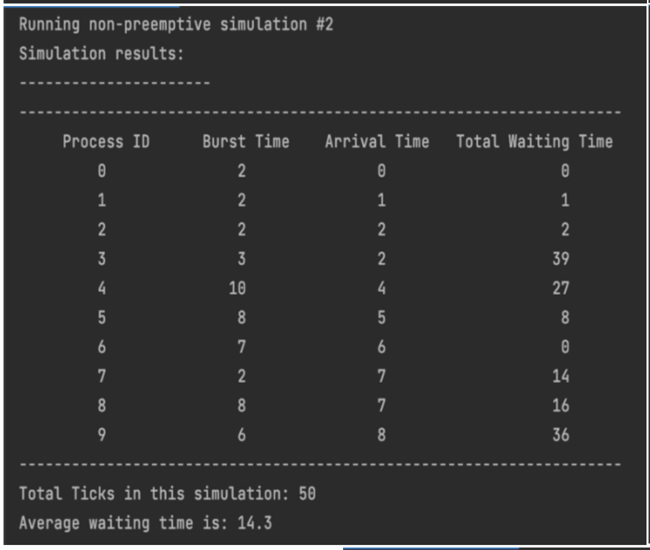
Test with seed* 29550455*:



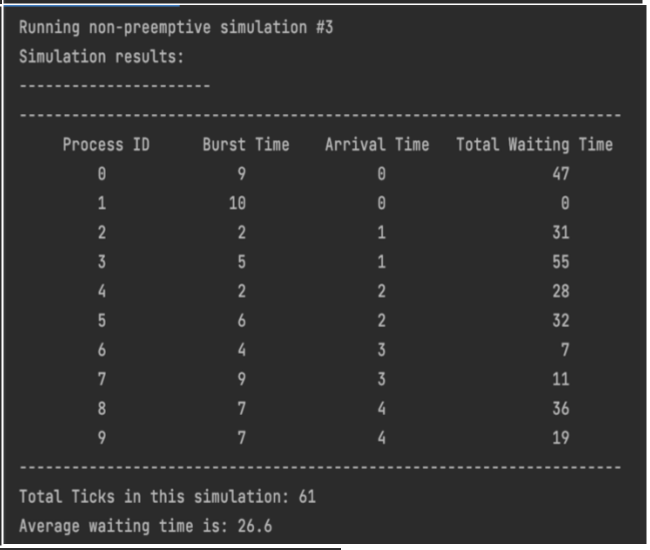
```
Running non-preemptive simulation #0
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               5              1                 0
         1               5              2                41
         2               9              3                 5
         3               7              3                26
         4               4              4                18
         5               2              4                 2
         6               3              5                21
         7               4              6                42
         8               5              7                10
         9               7              8                28
-----------------------------------------------------------------
Total Ticks in this simulation: 52
Average waiting time is: 19.3
```



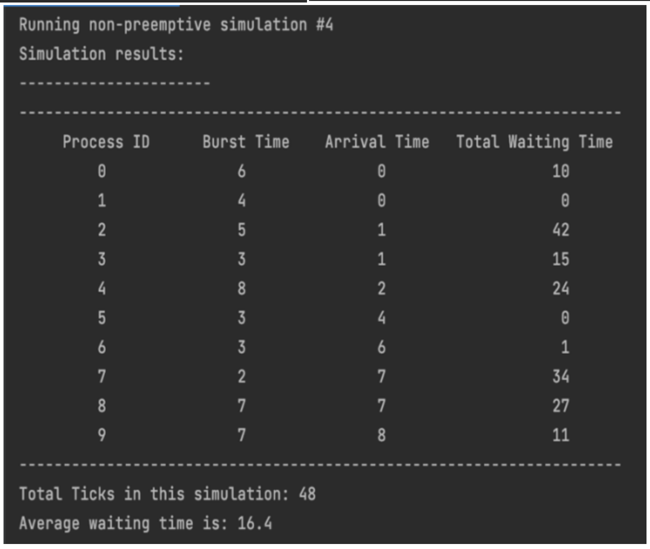
```
Running non-preemptive simulation #1
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              10              0                 0
         1              10              0                10
         2               9              1                58
         3               6              1                44
         4               3              2                27
         5               6              3                17
         6               8              3                48
         7               3              4                22
         8               7              6                32
         9               6              7                25
-----------------------------------------------------------------
Total Ticks in this simulation: 68
Average waiting time is: 28.3
```



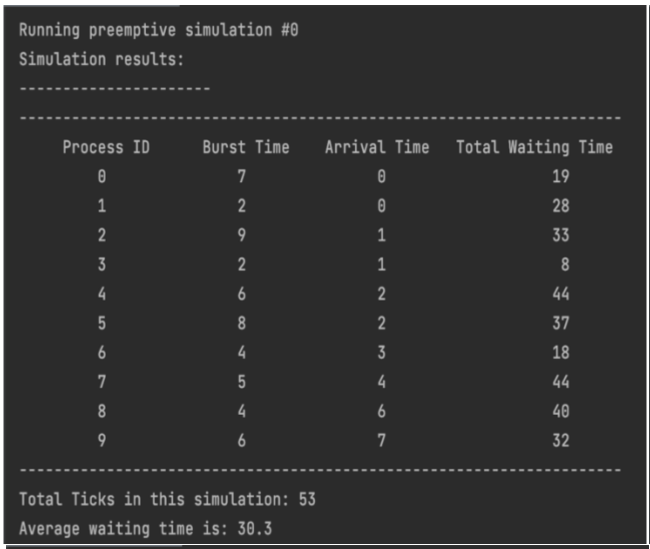
```
Running non-preemptive simulation #2
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               2              0                 0
         1               2              1                 1
         2               2              2                 2
         3               3              2                39
         4              10              4                27
         5               8              5                 8
         6               7              6                 0
         7               2              7                14
         8               8              7                16
         9               6              8                36
-----------------------------------------------------------------
Total Ticks in this simulation: 50
Average waiting time is: 14.3
```



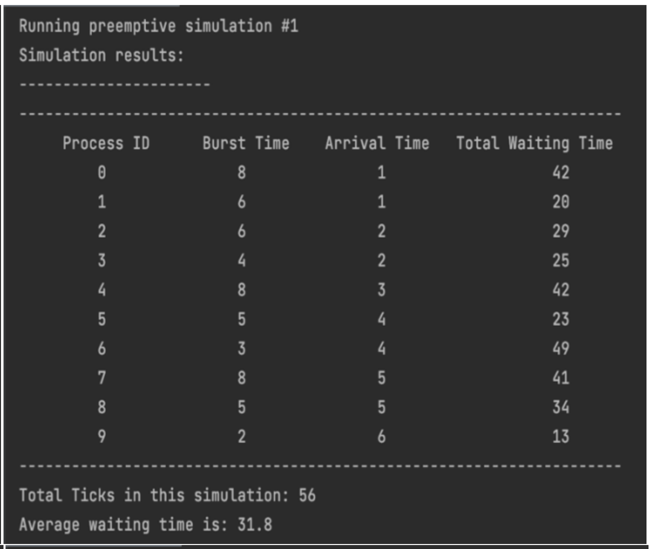
```
Running non-preemptive simulation #3
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               9              0                47
         1              10              0                 0
         2               2              1                31
         3               5              1                55
         4               2              2                28
         5               6              2                32
         6               4              3                 7
         7               9              3                11
         8               7              4                36
         9               7              4                19
-----------------------------------------------------------------
Total Ticks in this simulation: 61
Average waiting time is: 26.6
```



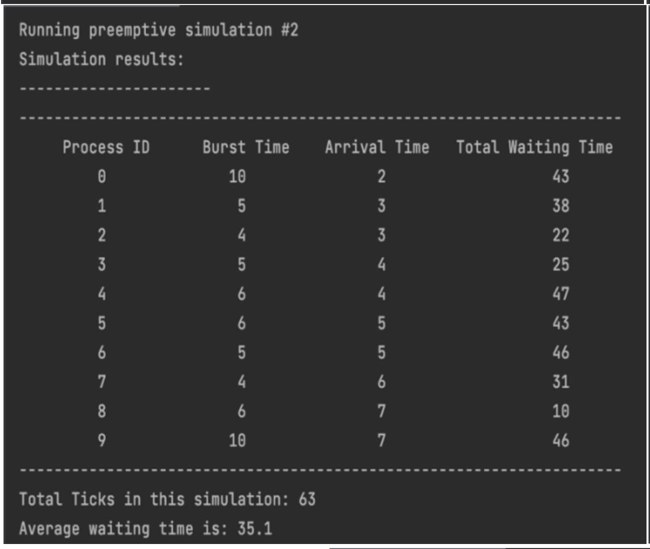
```
Running non-preemptive simulation #4
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               6              0                10
         1               4              0                 0
         2               5              1                42
         3               3              1                15
         4               8              2                24
         5               3              4                 0
         6               3              6                 1
         7               2              7                34
         8               7              7                27
         9               7              8                11
-----------------------------------------------------------------
Total Ticks in this simulation: 48
Average waiting time is: 16.4
```



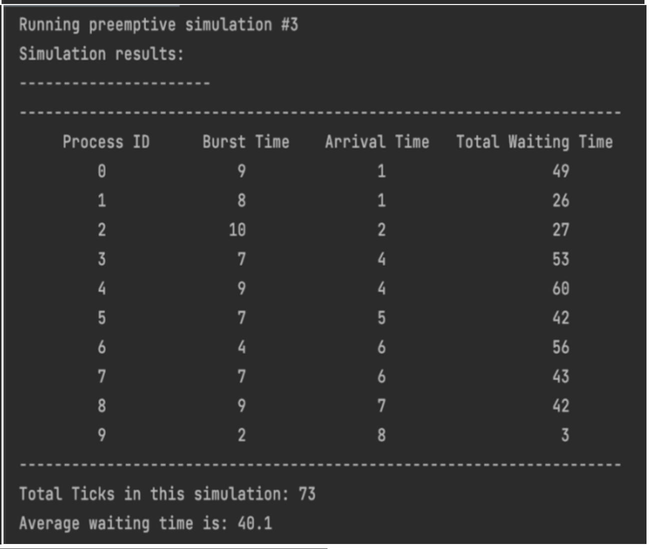
```
Running preemptive simulation #0
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID     Burst Time    Arrival Time   Total Waiting Time
         0              7              0                 19
         1              2              0                 28
         2              9              1                 33
         3              2              1                  8
         4              6              2                 44
         5              8              2                 37
         6              4              3                 18
         7              5              4                 44
         8              4              6                 40
         9              6              7                 32
-------------------------------------------------------------------
Total Ticks in this simulation: 53
Average waiting time is: 30.3
```



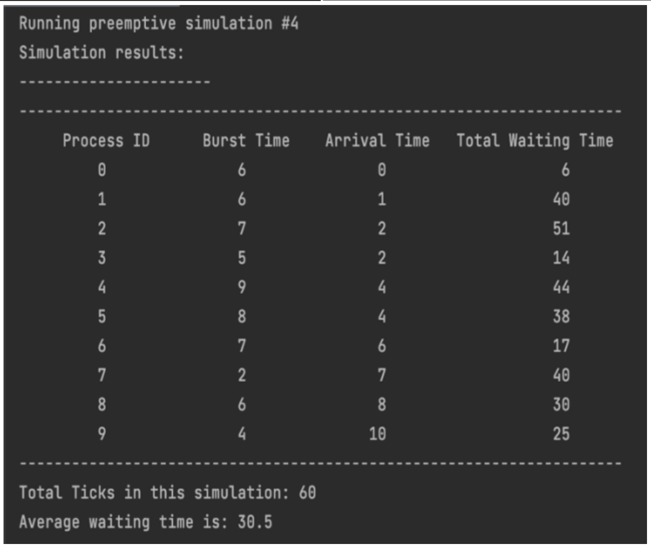
```
Running preemptive simulation #1
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID     Burst Time    Arrival Time   Total Waiting Time
         0              8              1                 42
         1              6              1                 20
         2              6              2                 29
         3              4              2                 25
         4              8              3                 42
         5              5              4                 23
         6              3              4                 49
         7              8              5                 41
         8              5              5                 34
         9              2              6                 13
-------------------------------------------------------------------
Total Ticks in this simulation: 56
Average waiting time is: 31.8
```



```
Running preemptive simulation #2
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID     Burst Time    Arrival Time   Total Waiting Time
         0             10              2                 43
         1              5              3                 38
         2              4              3                 22
         3              5              4                 25
         4              6              4                 47
         5              6              5                 43
         6              5              5                 46
         7              4              6                 31
         8              6              7                 10
         9             10              7                 46
-------------------------------------------------------------------
Total Ticks in this simulation: 63
Average waiting time is: 35.1
```

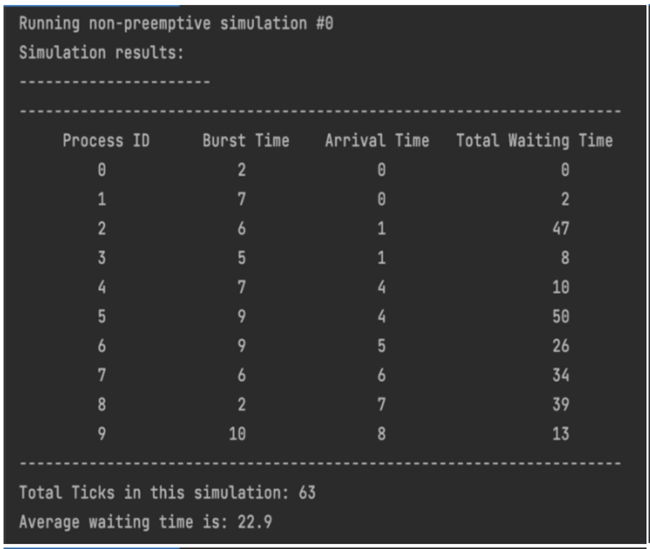


```
Running preemptive simulation #3
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID     Burst Time    Arrival Time   Total Waiting Time
         0              9              1                 49
         1              8              1                 26
         2             10              2                 27
         3              7              4                 53
         4              9              4                 60
         5              7              5                 42
         6              4              6                 56
         7              7              6                 43
         8              9              7                 42
         9              2              8                  3
-------------------------------------------------------------------
Total Ticks in this simulation: 73
Average waiting time is: 40.1
```

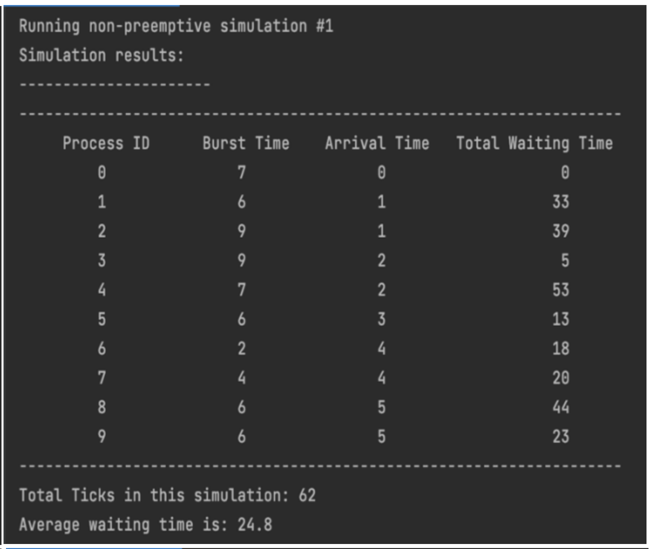


```
Running preemptive simulation #4
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID     Burst Time    Arrival Time   Total Waiting Time
         0              6              0                  6
         1              6              1                 40
         2              7              2                 51
         3              5              2                 14
         4              9              4                 44
         5              8              4                 38
         6              7              6                 17
         7              2              7                 40
         8              6              8                 30
         9              4             10                 25
-------------------------------------------------------------------
Total Ticks in this simulation: 60
Average waiting time is: 30.5
```

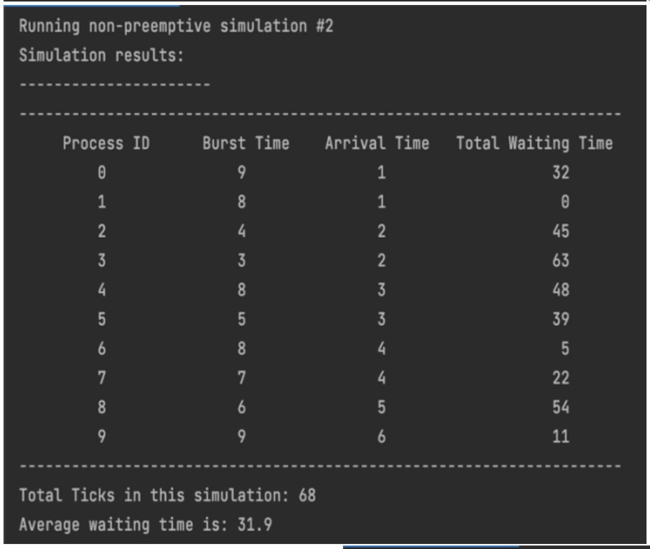
Test with seed* 16590675*:



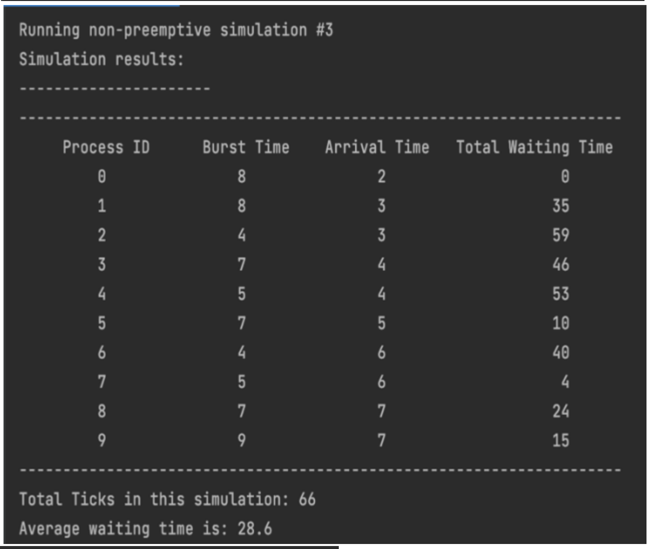
```
Running non-preemptive simulation #0
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              2              0                0
         1              7              0                2
         2              6              1               47
         3              5              1                8
         4              7              4               10
         5              9              4               50
         6              9              5               26
         7              6              6               34
         8              2              7               39
         9             10              8               13
-----------------------------------------------------------------
Total Ticks in this simulation: 63
Average waiting time is: 22.9
```



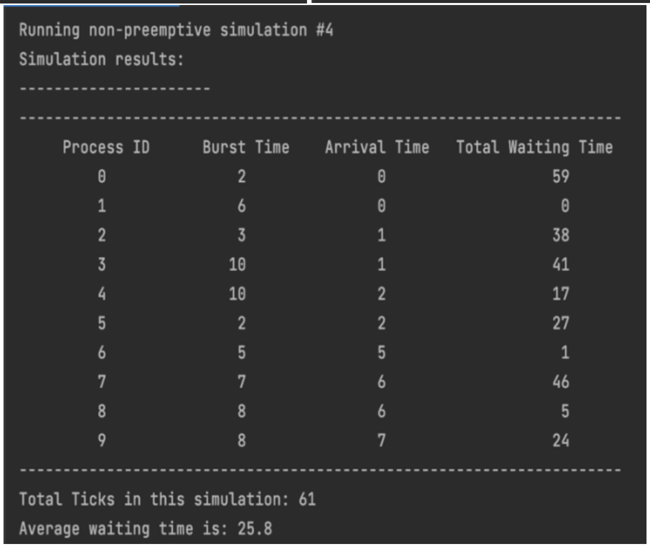
```
Running non-preemptive simulation #1
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              7              0                0
         1              6              1               33
         2              9              1               39
         3              9              2                5
         4              7              2               53
         5              6              3               13
         6              2              4               18
         7              4              4               20
         8              6              5               44
         9              6              5               23
-----------------------------------------------------------------
Total Ticks in this simulation: 62
Average waiting time is: 24.8
```



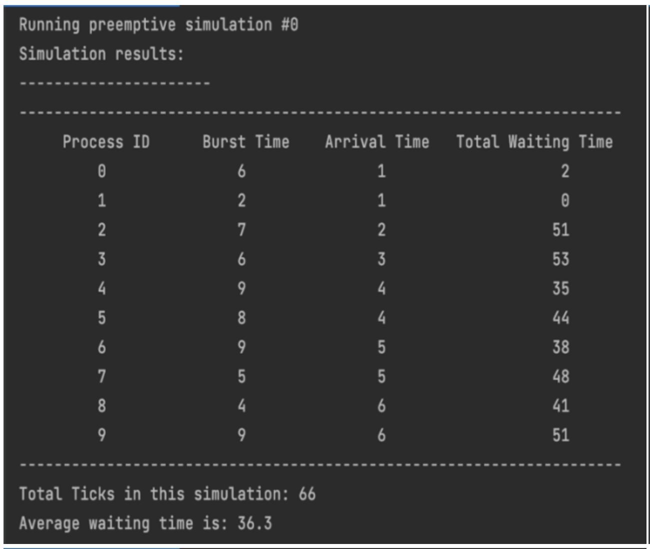
```
Running non-preemptive simulation #2
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              9              1               32
         1              8              1                0
         2              4              2               45
         3              3              2               63
         4              8              3               48
         5              5              3               39
         6              8              4                5
         7              7              4               22
         8              6              5               54
         9              9              6               11
-----------------------------------------------------------------
Total Ticks in this simulation: 68
Average waiting time is: 31.9
```



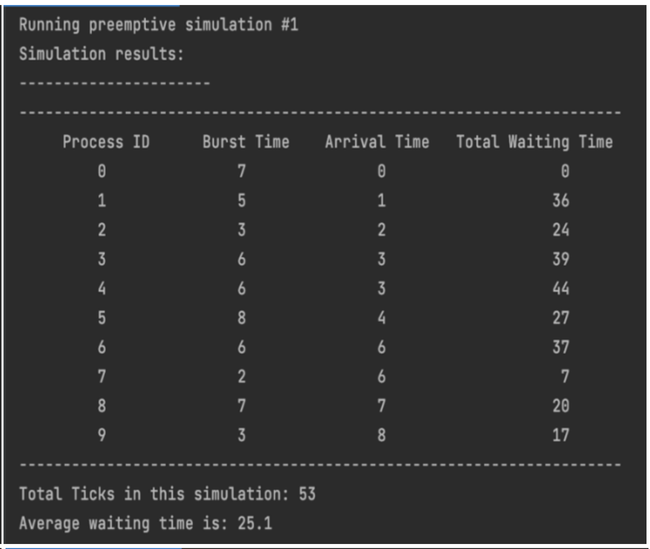
```
Running non-preemptive simulation #3
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              8              2                0
         1              8              3               35
         2              4              3               59
         3              7              4               46
         4              5              4               53
         5              7              5               10
         6              4              6               40
         7              5              6                4
         8              7              7               24
         9              9              7               15
-----------------------------------------------------------------
Total Ticks in this simulation: 66
Average waiting time is: 28.6
```



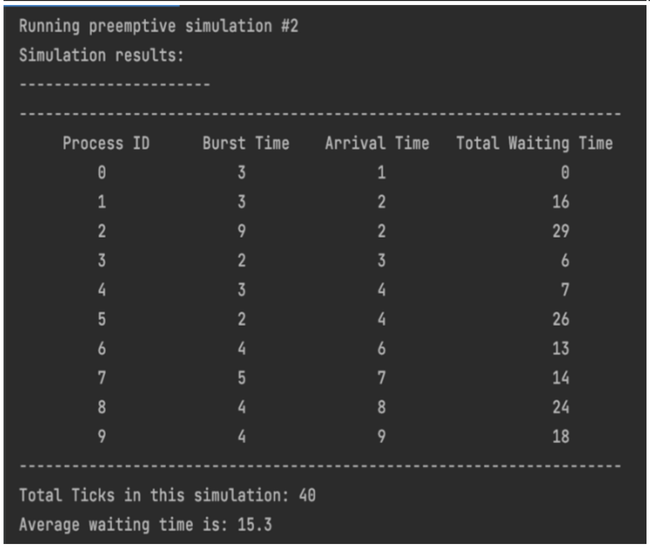
```
Running non-preemptive simulation #4
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0              2              0               59
         1              6              0                0
         2              3              1               38
         3             10              1               41
         4             10              2               17
         5              2              2               27
         6              5              5                1
         7              7              6               46
         8              8              6                5
         9              8              7               24
-----------------------------------------------------------------
Total Ticks in this simulation: 61
Average waiting time is: 25.8
```



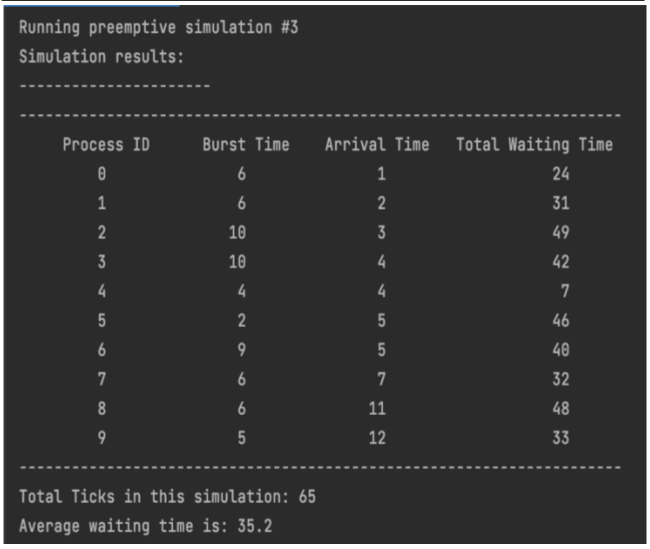
```
Running preemptive simulation #0
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               6              1                 2
         1               2              1                 0
         2               7              2                51
         3               6              3                53
         4               9              4                35
         5               8              4                44
         6               9              5                38
         7               5              5                48
         8               4              6                41
         9               9              6                51
-----------------------------------------------------------------
Total Ticks in this simulation: 66
Average waiting time is: 36.3
```



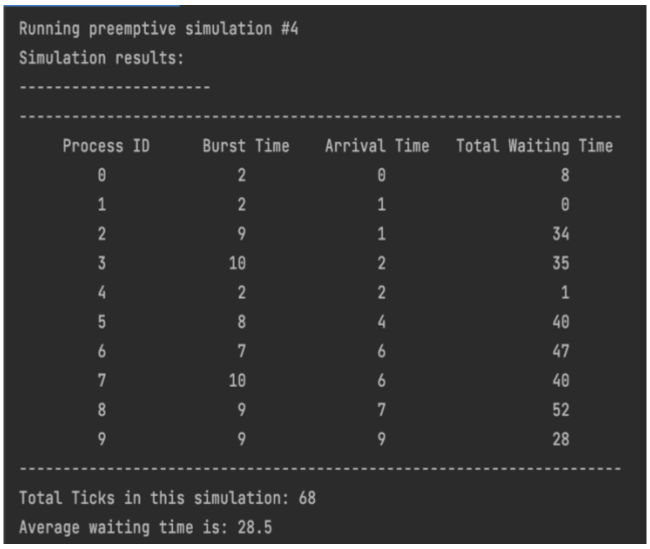
```
Running preemptive simulation #1
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               7              0                 0
         1               5              1                36
         2               3              2                24
         3               6              3                39
         4               6              3                44
         5               8              4                27
         6               6              6                37
         7               2              6                 7
         8               7              7                20
         9               3              8                17
-----------------------------------------------------------------
Total Ticks in this simulation: 53
Average waiting time is: 25.1
```



```
Running preemptive simulation #2
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               3              1                 0
         1               3              2                16
         2               9              2                29
         3               2              3                 6
         4               3              4                 7
         5               2              4                26
         6               4              6                13
         7               5              7                14
         8               4              8                24
         9               4              9                18
-----------------------------------------------------------------
Total Ticks in this simulation: 40
Average waiting time is: 15.3
```

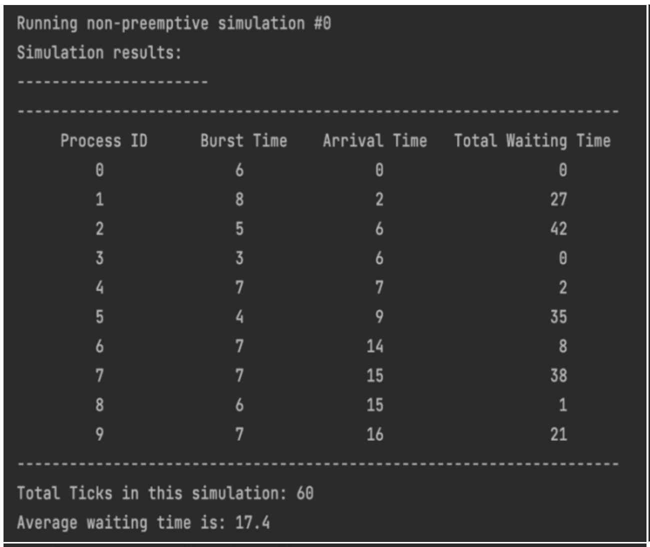


```
Running preemptive simulation #3
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               6              1                24
         1               6              2                31
         2              10              3                49
         3              10              4                42
         4               4              4                 7
         5               2              5                46
         6               9              5                40
         7               6              7                32
         8               6             11                48
         9               5             12                33
-----------------------------------------------------------------
Total Ticks in this simulation: 65
Average waiting time is: 35.2
```

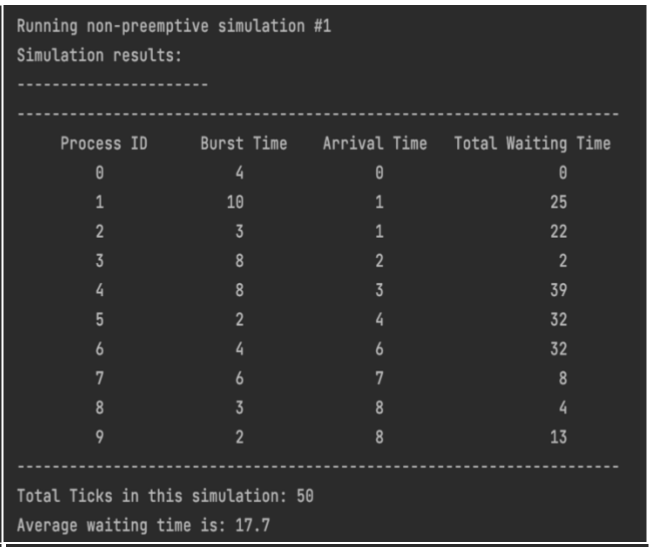


```
Running preemptive simulation #4
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               2              0                 8
         1               2              1                 0
         2               9              1                34
         3              10              2                35
         4               2              2                 1
         5               8              4                40
         6               7              6                47
         7              10              6                40
         8               9              7                52
         9               9              9                28
-----------------------------------------------------------------
Total Ticks in this simulation: 68
Average waiting time is: 28.5
```

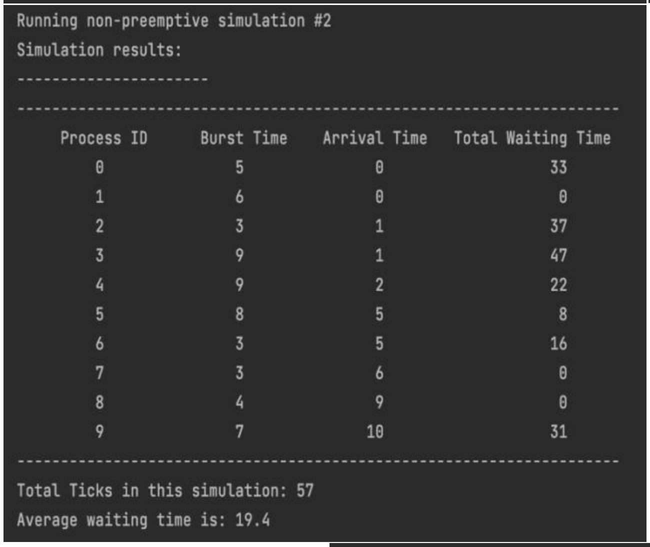
Test with seed* 13929885*:



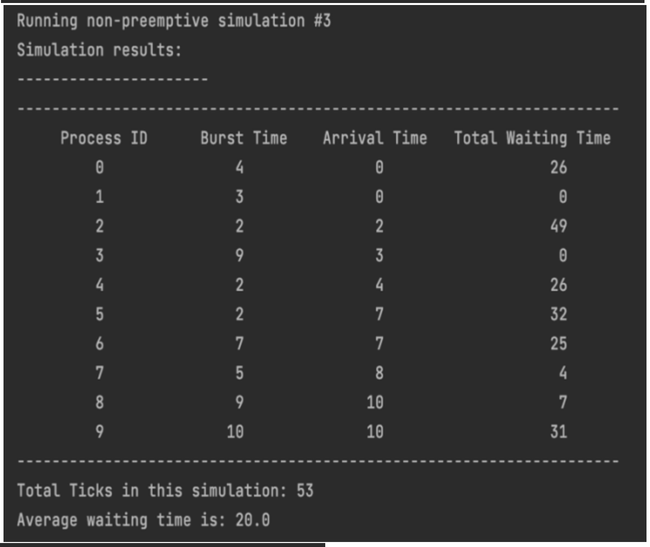
```
Running non-preemptive simulation #0
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               6              0                 0
         1               8              2                27
         2               5              6                42
         3               3              6                 0
         4               7              7                 2
         5               4              9                35
         6               7             14                 8
         7               7             15                38
         8               6             15                 1
         9               7             16                21
-----------------------------------------------------------------
Total Ticks in this simulation: 60
Average waiting time is: 17.4
```



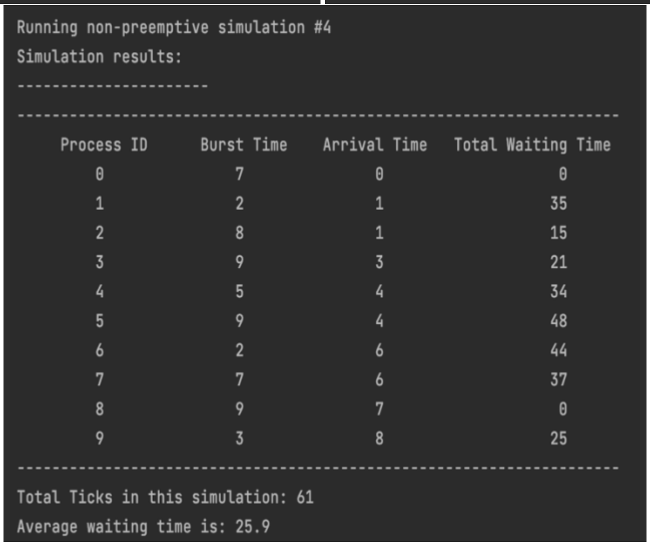
```
Running non-preemptive simulation #1
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               4              0                 0
         1              10              1                25
         2               3              1                22
         3               8              2                 2
         4               8              3                39
         5               2              4                32
         6               4              6                32
         7               6              7                 8
         8               3              8                 4
         9               2              8                13
-----------------------------------------------------------------
Total Ticks in this simulation: 50
Average waiting time is: 17.7
```



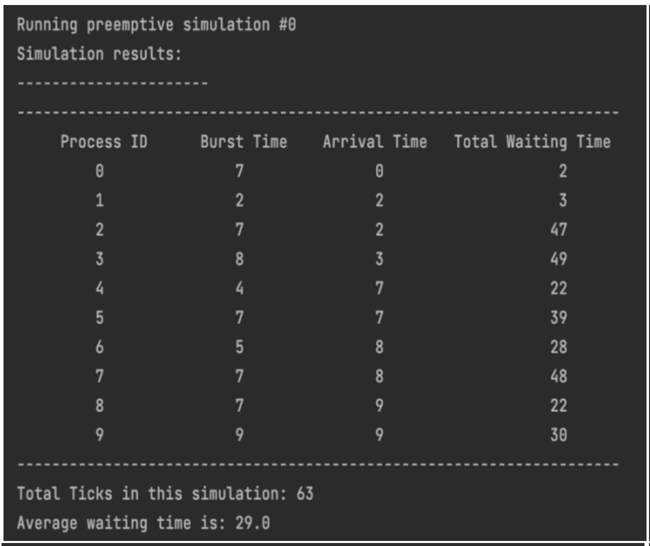
```
Running non-preemptive simulation #2
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               5              0                33
         1               6              0                 0
         2               3              1                37
         3               9              1                47
         4               9              2                22
         5               8              5                 8
         6               3              5                16
         7               3              6                 0
         8               4              9                 0
         9               7             10                31
-----------------------------------------------------------------
Total Ticks in this simulation: 57
Average waiting time is: 19.4
```



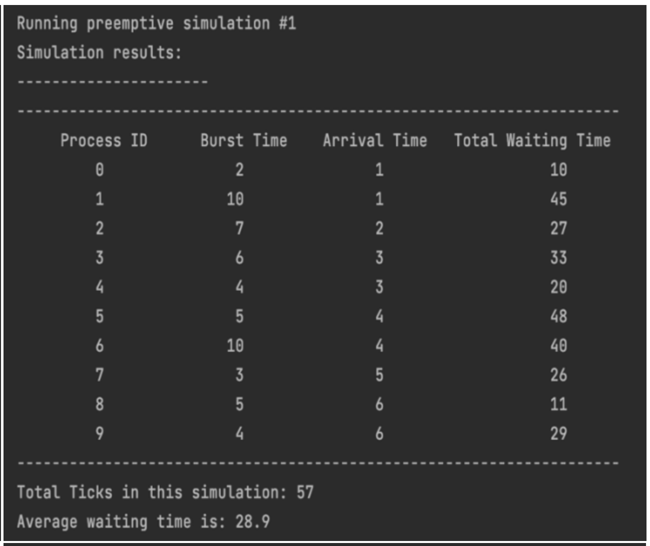
```
Running non-preemptive simulation #3
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               4              0                26
         1               3              0                 0
         2               2              2                49
         3               9              3                 0
         4               2              4                26
         5               2              7                32
         6               7              7                25
         7               5              8                 4
         8               9             10                 7
         9              10             10                31
-----------------------------------------------------------------
Total Ticks in this simulation: 53
Average waiting time is: 20.0
```



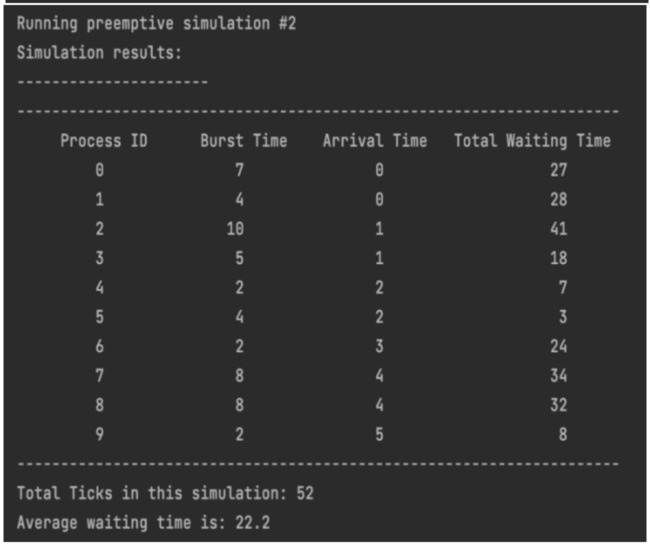
```
Running non-preemptive simulation #4
Simulation results:
---------------------
-----------------------------------------------------------------
     Process ID      Burst Time    Arrival Time   Total Waiting Time
         0               7              0                 0
         1               2              1                35
         2               8              1                15
         3               9              3                21
         4               5              4                34
         5               9              4                48
         6               2              6                44
         7               7              6                37
         8               9              7                 0
         9               3              8                25
-----------------------------------------------------------------
Total Ticks in this simulation: 61
Average waiting time is: 25.9
```



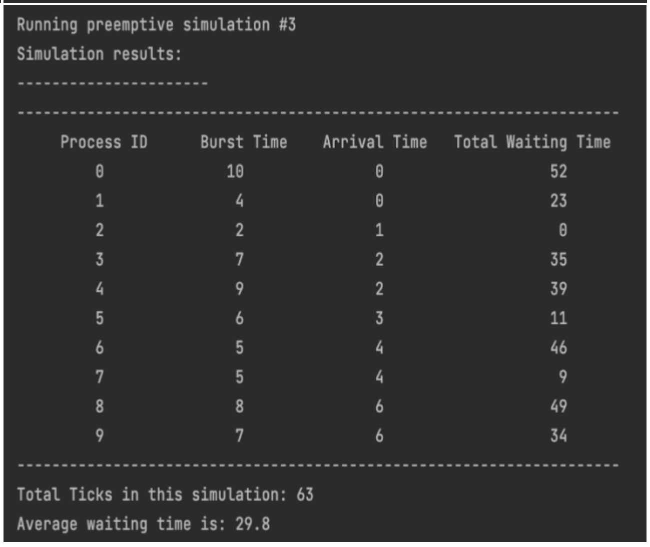
```
Running preemptive simulation #0
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID      Burst Time     Arrival Time   Total Waiting Time
          0               7               0                 2
          1               2               2                 3
          2               7               2                47
          3               8               3                49
          4               4               7                22
          5               7               7                39
          6               5               8                28
          7               7               8                48
          8               7               9                22
          9               9               9                30
-------------------------------------------------------------------
Total Ticks in this simulation: 63
Average waiting time is: 29.0
```



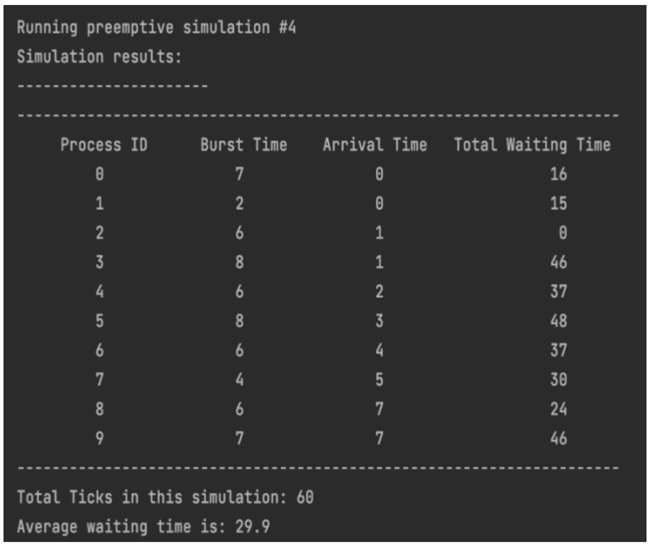
```
Running preemptive simulation #1
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID      Burst Time     Arrival Time   Total Waiting Time
          0               2               1                10
          1              10               1                45
          2               7               2                27
          3               6               3                33
          4               4               3                20
          5               5               4                48
          6              10               4                40
          7               3               5                26
          8               5               6                11
          9               4               6                29
-------------------------------------------------------------------
Total Ticks in this simulation: 57
Average waiting time is: 28.9
```



```
Running preemptive simulation #2
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID      Burst Time     Arrival Time   Total Waiting Time
          0               7               0                27
          1               4               0                28
          2              10               1                41
          3               5               1                18
          4               2               2                 7
          5               4               2                 3
          6               2               3                24
          7               8               4                34
          8               8               4                32
          9               2               5                 8
-------------------------------------------------------------------
Total Ticks in this simulation: 52
Average waiting time is: 22.2
```



```
Running preemptive simulation #3
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID      Burst Time     Arrival Time   Total Waiting Time
          0              10               0                52
          1               4               0                23
          2               2               1                 0
          3               7               2                35
          4               9               2                39
          5               6               3                11
          6               5               4                46
          7               5               4                 9
          8               8               6                49
          9               7               6                34
-------------------------------------------------------------------
Total Ticks in this simulation: 63
Average waiting time is: 29.8
```



```
Running preemptive simulation #4
Simulation results:
---------------------
-------------------------------------------------------------------
     Process ID      Burst Time     Arrival Time   Total Waiting Time
          0               7               0                16
          1               2               0                15
          2               6               1                 0
          3               8               1                46
          4               6               2                37
          5               8               3                48
          6               6               4                37
          7               4               5                30
          8               6               7                24
          9               7               7                46
-------------------------------------------------------------------
Total Ticks in this simulation: 60
Average waiting time is: 29.9
```