

# COEN 241 HW1

## 1. Detailed information of experiment device



Figure 1 detailed information

CPU: Intel Core i5 2.4GHz, Quad-Core

Memory: 8GB

## 2. Steps for enabling QEMU container

a. Install QEMU on Mac using command:

```
brew install qemu
```

b. Create QEMU image using command:

```
sudo qemu-img create ubuntu.img 10G -f qcow2
```

```
(base) Haoyuan@Haoyuans-MacBook-Pro-5 ~ % sudo qemu-img create ubuntu.img 10G -f qcow2
Password:
Formatting 'ubuntu.img', fmt=qcow2 cluster_size=65536 extended_l2=off compression_type=zlib size=10737418240 lazy_refcounts=off refcount_bits=16
```

Figure 2 execution output

c. Install the VM using command:

```
sudo qemu-system-x86_64 -hda ubuntu.img -boot d -cdrom
```

```
/Users/Haoyuan/Downloads/ubuntu-20.04.5-live-server-amd64.iso -m 2046 -boot strict=on
```

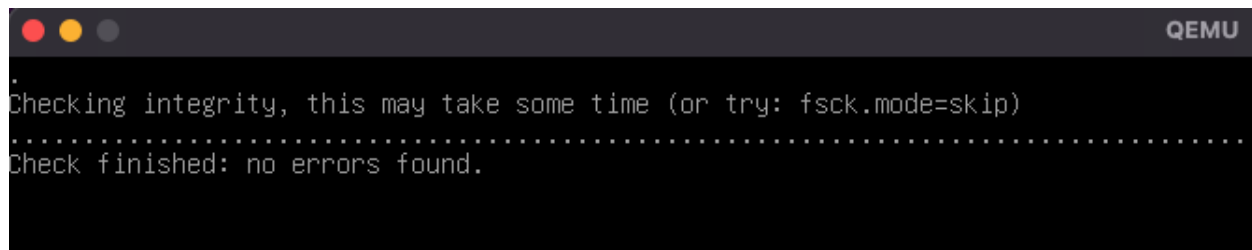


Figure 3 integrity check

d. Wait for the integrity check and then configure the VM:

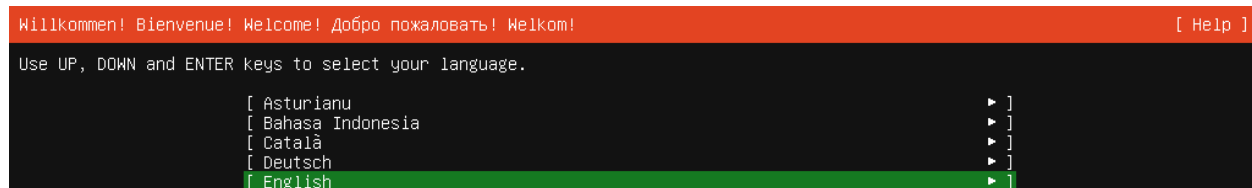


Figure 4 configuration

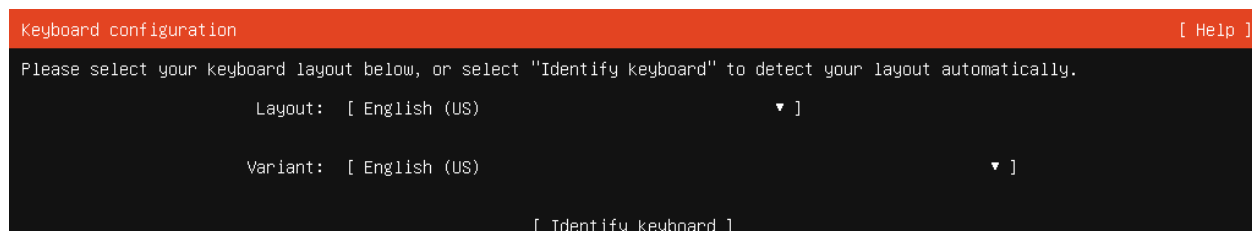


Figure 5 configuration

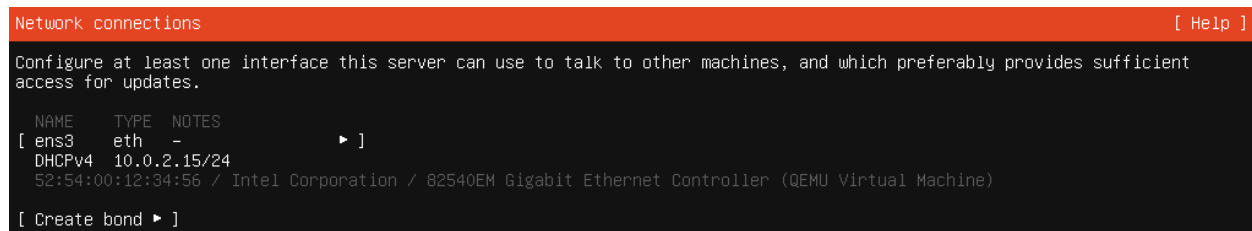


Figure 6 configuration

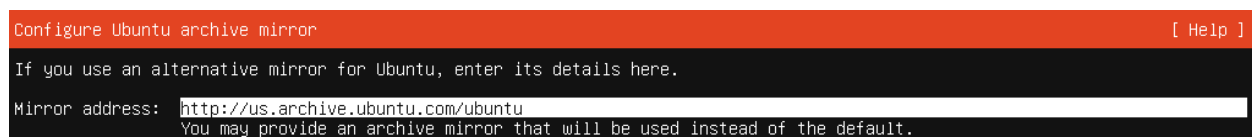


Figure 7 configuration

```
Guided storage configuration [ Help ]
Configure a guided storage layout, or create a custom one:

(X) Use an entire disk
    [ QEMU_HARDDISK_QM00001 local disk 10.000G ▼ ]
    [X] Set up this disk as an LVM group
        [ ] Encrypt the LVM group with LUKS
            Passphrase:
            Confirm passphrase:

( ) Custom storage layout
```

Figure 8 configuration

```
Storage configuration [ Help ]
FILE SYSTEM SUMMARY
MOUNT POINT    SIZE    TYPE    DEVICE TYPE
[ /             8.246G  new ext4  new LVM logical volume ▶ ]
[ /boot         1.750G  new ext4  new partition of local disk ▶ ]

AVAILABLE DEVICES
No available devices
[ Create software RAID (md) ▶ ]
[ Create volume group (LVM) ▶ ]

USED DEVICES
DEVICE                                TYPE                                SIZE
[ ubuntu-vg (new)                     LVM volume group                   8.246G ▶ ]
ubuntu-lv    new, to be formatted as ext4, mounted at /  8.246G ▶ ]
[ QEMU_HARDDISK_QM00001                local disk                          10.000G ▶ ]
partition 1  new, BIOS grub spacer      1.000M ▶ ]
partition 2  new, to be formatted as ext4, mounted at /boot  1.750G ▶ ]
partition 3  new, PV of LVM volume group ubuntu-vg           8.247G ▶ ]
```

Figure 9 configuration

```
Profile setup [ Help ]
Enter the username and password you will use to log in to the system. You can configure SSH access on the next screen but a password is still needed for sudo.

Your name: Haoyuan Zhai

Your server's name: hzhai96
The name it uses when it talks to other computers.

Pick a username: hzhai96

Choose a password: *****

Confirm your password: *****
```

Figure 10 configuration

For other configuration, leave blank.

e. Start the VM in terminal using command:

```
sudo qemu-system-x86_64 -hda ubuntu.img -m 2046
```



Figure 11 successfully booted

### 3. Steps for enabling Docker container

- a. Pull the latest version of Ubuntu image using command:

`docker pull ubuntu`

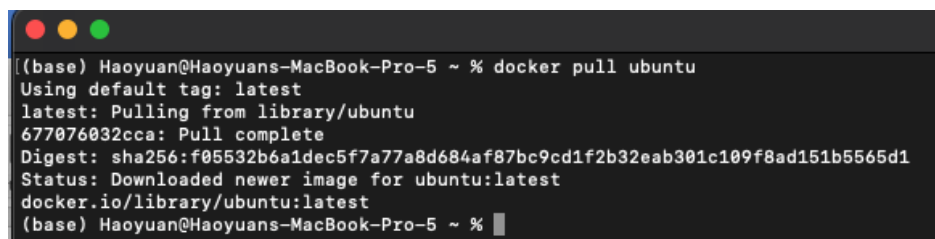


Figure 12 pull latest ubuntu image

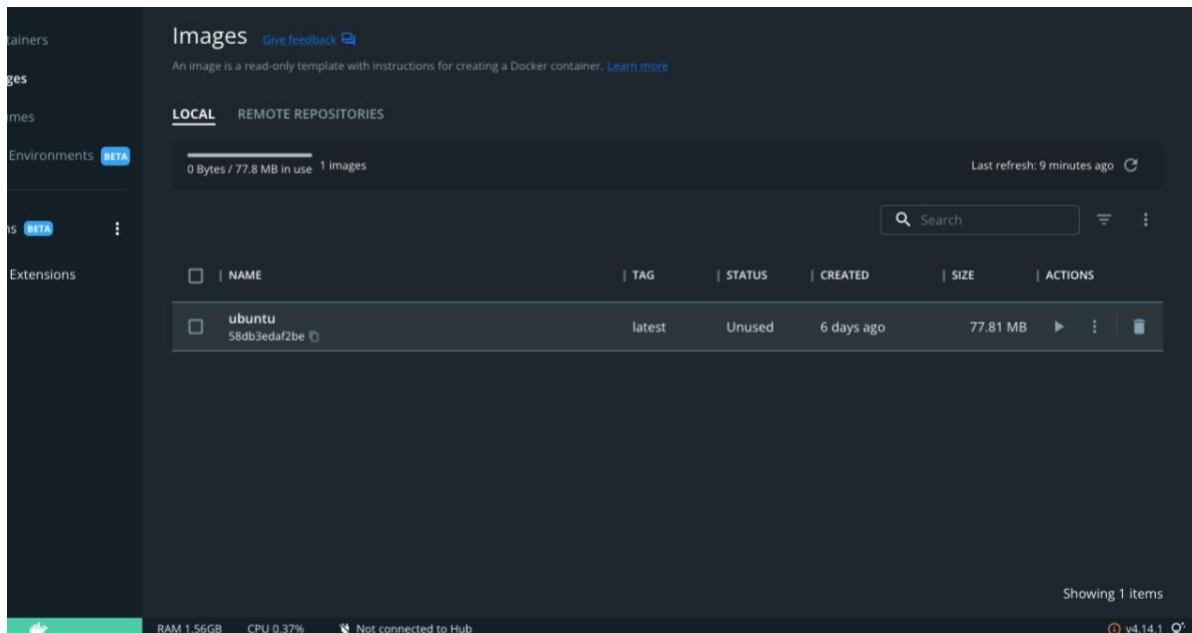


Figure 13 ubuntu image in Docker

- b. Create a new container “myUbuntu” based on the Ubuntu image using command:

`docker run --name myUbuntu -it ubuntu:latest bash`

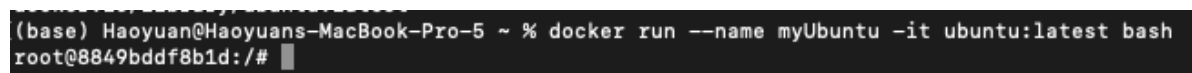


Figure 14 execution output

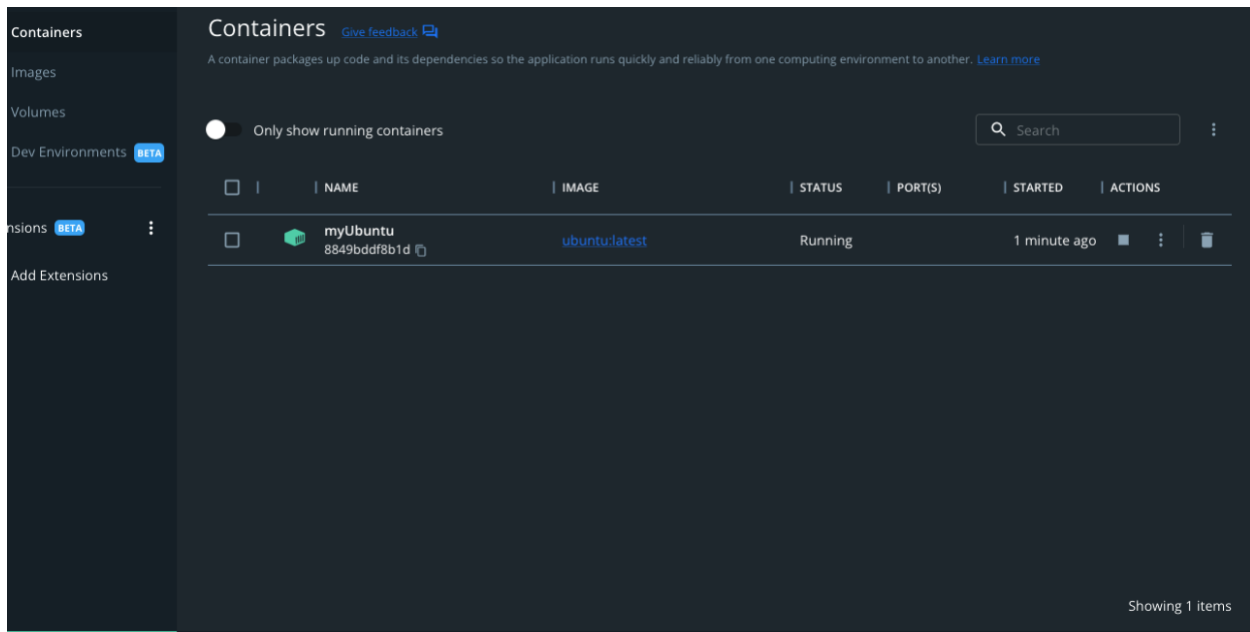


Figure 15 container in Docker

- c. In the Ubuntu command line, update the package sources list with the latest versions of the packages in the repositories using command:

`apt update`

```
root@8849bddf8b1d:/# apt update
Get:1 http://security.ubuntu.com/ubuntu jammy-security InRelease [110 kB]
Get:2 http://archive.ubuntu.com/ubuntu jammy InRelease [270 kB]
Get:3 http://security.ubuntu.com/ubuntu jammy-security/main amd64 Packages [753 kB]
Get:4 http://archive.ubuntu.com/ubuntu jammy-updates InRelease [114 kB]
Get:5 http://archive.ubuntu.com/ubuntu jammy-backports InRelease [99.8 kB]
Get:6 http://archive.ubuntu.com/ubuntu jammy/restricted amd64 Packages [164 kB]
Get:7 http://archive.ubuntu.com/ubuntu jammy/main amd64 Packages [1792 kB]
Get:8 http://security.ubuntu.com/ubuntu jammy-security/restricted amd64 Packages [681 kB]
Get:9 http://security.ubuntu.com/ubuntu jammy-security/multiverse amd64 Packages [4732 B]
Get:10 http://security.ubuntu.com/ubuntu jammy-security/universe amd64 Packages [798 kB]
Get:11 http://archive.ubuntu.com/ubuntu jammy/multiverse amd64 Packages [266 kB]
Get:12 http://archive.ubuntu.com/ubuntu jammy/universe amd64 Packages [17.5 MB]
Get:13 http://archive.ubuntu.com/ubuntu jammy-updates/restricted amd64 Packages [730 kB]
Get:14 http://archive.ubuntu.com/ubuntu jammy-updates/multiverse amd64 Packages [8978 B]
Get:15 http://archive.ubuntu.com/ubuntu jammy-updates/universe amd64 Packages [1007 kB]
Get:16 http://archive.ubuntu.com/ubuntu jammy-updates/main amd64 Packages [1078 kB]
Get:17 http://archive.ubuntu.com/ubuntu jammy-backports/universe amd64 Packages [7284 B]
Get:18 http://archive.ubuntu.com/ubuntu jammy-backports/main amd64 Packages [3520 B]
Fetched 25.4 MB in 4s (6196 kB/s)
Reading package lists... Done
Building dependency tree... Done
Reading state information... Done
All packages are up to date.
root@8849bddf8b1d:/#
```

Figure 16 execution output

- d. Install sysbench using command:

`apt install sysbench`

```

root@8849bddf8b1d:/# apt install sysbench
Reading package lists... Done
Building dependency tree... Done
Reading state information... Done
The following additional packages will be installed:
  libaio1 libldap-2.5-0 libldap-common liblua5.1-2 liblua5.1-common libmysqlclient21
Suggested packages:
  libsasl2-modules-gssapi-mit | libsasl2-modules-gssapi-heimdal libsasl2-modules-ldap libsasl2-modules-sql
The following NEW packages will be installed:
  libaio1 libldap-2.5-0 libldap-common liblua5.1-2 liblua5.1-common libmysqlclient21
0 upgraded, 12 newly installed, 0 to remove and 0 not upgraded.
Need to get 2187 kB of archives.
After this operation, 9732 kB of additional disk space will be used.
Do you want to continue? [Y/n] y

```

Figure 17 execution output

- e. Test if sysbench has been correctly installed using command:

`sysbench --version`

```

root@8849bddf8b1d:/# sysbench --version
sysbench 1.0.20
root@8849bddf8b1d:/#

```

Figure 18 execution output

- f. Install necessary tools to collect performance data using command:

`apt-get install sysstat`

`apt-get install net-tools`

## 4. Test different arguments of QEMU

I have tested two different arguments of qemu.

### a. “-m” argument

I used the argument -m to set the amount of memory. The amount of the memory is set to 20. And after installing the VM, I used “free” command to check the memory of the VM.

	total	used	free	shared	buff/cache	available
Mem:	2028892	140156	1416580	948	472156	1732308
Swap:	1540092	0	1540092			

Figure 19 execution output

### b. “-accel tcg” argument

I used the argument -accel to test out the function for this argument. The accelerating method I chose is TCG, which is Tiny Code Generator.

After installing, I used “top” command to monitor the CPU utilization. By testing, the VM shows that it has a better performance in CPU utilization.

## 5. System performance

### Scenario 1: CPU utilization

In both QEMU and Docker Ubuntu, we can use the command “top” to see the CPU utilization.

#### a. Collect CPU utilization in QEMU Ubuntu

```
top - 23:12:35 up 2 min, 1 user, load average: 4.21, 2.37, 0.91
Tasks: 94 total, 1 running, 93 sleeping, 0 stopped, 0 zombie
%Cpu(s): 0.3 us, 1.3 sy, 0.0 ni, 98.4 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
MiB Mem : 1981.3 total, 1527.5 free, 126.8 used, 327.0 buff/cache
MiB Swap: 1504.0 total, 1504.0 free, 0.0 used, 1706.0 avail Mem
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
988	hzhai96	20	0	9260	3852	3184	R	1.3	0.2	0:00.38	top
525	root	rt	0	280308	18120	8208	S	0.3	0.9	0:00.23	multipathd
686	root	20	0	0	0	0	I	0.3	0.0	0:00.48	kworker/0:4-events
1	root	20	0	168116	11256	8252	S	0.0	0.6	0:08.66	systemd
2	root	20	0	0	0	0	S	0.0	0.0	0:00.02	kthreadd
3	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	rcu_gp
4	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	rcu_par_gp
5	root	20	0	0	0	0	I	0.0	0.0	0:00.05	kworker/0:0-cgroup_destroy
6	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	kworker/0:0H
7	root	20	0	0	0	0	I	0.0	0.0	0:00.02	kworker/u2:0-events_unbound
8	root	0	-20	0	0	0	I	0.0	0.0	0:00.00	mm_percpu_wq
9	root	20	0	0	0	0	S	0.0	0.0	0:00.83	ksoftirqd/0
10	root	20	0	0	0	0	I	0.0	0.0	0:02.99	rcu_sched
11	root	rt	0	0	0	0	S	0.0	0.0	0:00.00	migration/0
12	root	-51	0	0	0	0	S	0.0	0.0	0:00.00	idle_inject/0
13	root	20	0	0	0	0	I	0.0	0.0	0:02.31	kworker/0:1-events

Figure 20 execution output

We can see from the figure that there are totally 94 tasks currently. One is running, the other 93 tasks are sleeping. In the %CPUs part, 0.3% of CPU is used for user-level, and 1.3% is used for kernel-level.

#### b. Collect CPU utilization in Docker Ubuntu

```
top - 22:46:15 up 19 min, 0 users, load average: 0.00, 0.26, 0.48
Tasks: 5 total, 1 running, 4 sleeping, 0 stopped, 0 zombie
%Cpu(s): 0.1 us, 0.3 sy, 0.0 ni, 99.7 id, 0.0 wa, 0.0 hi, 0.0 si, 0.0 st
MiB Mem : 3933.5 total, 114.5 free, 257.2 used, 3561.7 buff/cache
MiB Swap: 1024.0 total, 1022.5 free, 1.5 used, 3089.3 avail Mem
```

PID	USER	PR	NI	VIRT	RES	SHR	S	%CPU	%MEM	TIME+	COMMAND
1	root	20	0	4624	3296	2836	S	0.0	0.1	0:00.06	bash
9	root	20	0	2888	1024	928	S	0.0	0.0	0:00.01	sh
15	root	20	0	2888	932	844	S	0.0	0.0	0:00.01	sh
21	root	20	0	2888	952	856	S	0.0	0.0	0:00.03	sh
59	root	20	0	7324	3212	2636	R	0.0	0.1	0:00.24	top

Figure 21 execution output

We can see from the figure that there are totally 5 tasks currently. One is running, the other 4 tasks are sleeping. In the %CPUs part, 0.1% of CPU is used for user-level, and 0.3% is used for kernel-level.

### Scenario 2: Disk I/O performance

In both QEMU and Docker Ubuntu, we can use the command “iostat” to see the average I/O performance of the system's disks.

#### a. Collect disk I/O performance in QEMU Ubuntu

```
Linux 5.4.0-137-generic (hzhai96) 02/01/2023 _x86_64_ (1 CPU)
avg-cpu:  %user   %nice %system %iowait  %steal   %idle
           24.95    4.39   21.89    0.44    0.00   48.33

Device            tps    kB_read/s    kB_wrtn/s    kB_dscd/s    kB_read    kB_wrtn    kB_dscd
dm-0              43.58      1088.17       85.70        0.00     330117     26000      0
fd0               0.02        0.07        0.00        0.00         20         0         0
loop0            4.97        5.94        0.00        0.00       1802         0         0
loop1            0.14        1.11        0.00        0.00        336         0         0
loop2           66.14       67.11        0.00        0.00     20358         0         0
loop3            0.18        3.50        0.00        0.00       1062         0         0
loop4            0.23        3.55        0.00        0.00       1078         0         0
loop5            0.00        0.00        0.00        0.00          1         0         0
sda              32.18     1120.21      84.24        0.00    339838     25556      0
```

Figure 22 execution output

The figure shows that the average CPU utilization percentage for user-level processes is 24.95%. For kernel-level, it's 21.89%. For I/O waiting, it's 0.44%. For not being used, it's 38.33%.

For the disk device dm-0, the transactions per second is 43.58, the kB for read per second is 1088.17kb, for write it's 85.7. The kB that has been read is 330117, for written it's 26000kb.

For the disk device fd0, the transactions per second is 0.02, the kB for read per second is 0.07kb, for write it's 0. The kB that has been read is 20kB, for written it's 0kB.

#### ***b. Collect disk I/O performance in Docker Ubuntu***

```
Linux 5.15.49-linuxkit (8849bddf8b1d) 02/01/23 _x86_64_ (4 CPU)
avg-cpu:  %user   %nice %system %iowait  %steal   %idle
           0.45    0.00    3.90    8.64    0.00   87.00

Device            tps    kB_read/s    kB_wrtn/s    kB_dscd/s    kB_read    kB_wrtn    kB_dscd
vda              2091.15      236.24     25729.57        0.00     353867     38540832      0
```

Figure 23 execution output

The figure shows that the average CPU utilization percentage for user-level processes is 0.45%. For kernel-level, it's 3.90%. For I/O waiting, it's 8.64%. For not being used, it's 87%.

For the disk device vda, the transactions per second is 2091.15, kB for read per second is 236.24kb, for write it's 25729.57kb. The kB that has been read is 353867kb, for written it's 38540832 kb.

### **Scenario 3: Memory usage**

In both QEMU and Docker Ubuntu, we can use the command “free” to see the system's total available and used memory, as well as swap space.

#### ***a. Collect memory usage in QEMU Ubuntu***

```
Mem:          total        used        free      shared  buff/cache   available
Swap:        1540092         0      1540092
```

Figure 24 execution output

The figure shows that the total physical memory of the system is 2028892kB. 140156kB are used. 1416580kB are still available. 948kB are shared between processes. 472156kB are used as buffer and cache. 1732308kB are available including cache and buffer.



For the swap space usage, there are 1540092kB in total. 0kB are in use. And 1540092kB are free to use.

#### ***b. Collect memory usage in Docker Ubuntu***

	total	used	free	shared	buff/cache	available
Mem:	4027864	306460	206832	340176	3514572	3113916
Swap:	1048572	2072	1046500			

Figure 25 execution output

The figure shows that the total physical memory of the system is 4027864kB. 306460kB are used. 206832kB are still available. 340176kB are shared between processes. 3514572kB are used as buffer and cache. 3113916kB are available including cache and buffer.

For the swap space usage, there are 1048572kB in total. 2072kB are in use. And 1046500kB are free to use.

## **6. Sysbench test under CPU mode**

For this part of the experiment, I will conduct CPU performance test using sysbench in both QEMU Ubuntu and Docker Ubuntu. The experiment is conducted with 4 different testcases:

Single-threaded CPU performance test.

Multi-threaded CPU performance test.

Single threaded CPU performance test with large maximum prime number.

Multithreaded CPU performance test with large maximum prime number.

### **Test case 1: Single-threaded CPU performance test**

Object: test out CPU performance with single thread.

The shell script that I created for this scenario:

```
#!/bin/sh
sysbench cpu --cpu-max-prime=100 --time=40 run
```

Figure 26 shell script

After test, the maximum prime number is set to 100, and the time limit is set to 40. In this case, there will be more time spent on doing I/O, so the execution time will be smaller than the time limit.

#### ***a. Results for executing five times in QEMU Ubuntu:***

```

CPU speed:
  events per second: 149784.38

General statistics:
  total time:          40.0005s
  total number of events: 5991982

Latency (ms):
  min:          0.01
  avg:          0.01
  max:          7.39
  95th percentile: 0.01
  sum:          34375.42

Threads fairness:
  events (avg/stddev): 5991982.0000/0.00
  execution time (avg/stddev): 34.3754/0.00

```

Figure 27 1<sup>st</sup> execution

```

CPU speed:
  events per second: 150592.76

General statistics:
  total time:          40.0004s
  total number of events: 6024282

Latency (ms):
  min:          0.01
  avg:          0.01
  max:          5.36
  95th percentile: 0.01
  sum:          34409.88

Threads fairness:
  events (avg/stddev): 6024282.0000/0.00
  execution time (avg/stddev): 34.4099/0.00

```

Figure 28 2<sup>nd</sup> execution

```

CPU speed:
  events per second: 146586.89

General statistics:
  total time:          40.0004s
  total number of events: 5864047

Latency (ms):
  min:          0.01
  avg:          0.01
  max:          8.38
  95th percentile: 0.01
  sum:          34433.88

Threads fairness:
  events (avg/stddev): 5864047.0000/0.00
  execution time (avg/stddev): 34.4339/0.00

```

Figure 29 3<sup>rd</sup> execution

```

CPU speed:
  events per second: 146798.06

General statistics:
  total time:          40.0004s
  total number of events: 5872437

Latency (ms):
  min:          0.01
  avg:          0.01
  max:          7.52
  95th percentile: 0.01
  sum:          34320.77

Threads fairness:
  events (avg/stddev): 5872437.0000/0.00
  execution time (avg/stddev): 34.3208/0.00

```

Figure 30 4<sup>th</sup> execution

```

CPU speed:
  events per second: 144685.70

General statistics:
  total time:          40.0004s
  total number of events: 5787979

Latency (ms):
  min:          0.01
  avg:          0.01
  max:          8.12
  95th percentile: 0.01
  sum:          34136.01

Threads fairness:
  events (avg/stddev): 5787979.0000/0.00
  execution time (avg/stddev): 34.1360/0.00

```

Figure 31 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Events/sec</b>	149784.38	150592.76	146586.89	146798.06	144695.70
<b>Total # of events</b>	5991982	6024282	5864047	5872437	5787979
<b>Min latency (ms)</b>	0.01	0.01	0.01	0.01	0.01
<b>Avg latency (ms)</b>	0.01	0.01	0.01	0.01	0.01
<b>Max latency (ms)</b>	7.39	5.36	8.38	7.52	8.12
<b>Execution time (s)</b>	34.3754	34.4099	34.4339	34.3208	34.1360

	Min	Max	Mean	Variance
Events/sec	144695.7	150592.76	147691.558	4758134.44
Total # of events	5787979	6024282	5908145.4	7635201552
Min latency (ms)	0.01	0.01	0.01	0
Avg latency (ms)	0.01	0.01	0.01	0
Max latency (ms)	5.36	8.38	7.354	1.128864
Execution time (s)	34.136	34.4339	34.3352	0.01136516

*b. Results for executing five times in Docker Ubuntu:*

```

CPU speed:
  events per second: 845823.89

General statistics:
  total time:          40.0002s
  total number of events: 33834363

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                3.88
  95th percentile:    0.00
  sum:                36656.12

Threads fairness:
  events (avg/stddev): 33834363.0000/0.00
  execution time (avg/stddev): 36.6561/0.00

```

Figure 32 1<sup>st</sup> execution

```

CPU speed:
  events per second: 829241.50

General statistics:
  total time:          40.0001s
  total number of events: 33170874

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                7.94
  95th percentile:    0.00
  sum:                36631.50

Threads fairness:
  events (avg/stddev): 33170874.0000/0.00
  execution time (avg/stddev): 36.6315/0.00

```

Figure 33 2<sup>nd</sup> execution

```

CPU speed:
  events per second: 835851.67

General statistics:
  total time:          40.0001s
  total number of events: 33435571

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                1.71
  95th percentile:    0.00
  sum:                36647.70

Threads fairness:
  events (avg/stddev): 33435571.0000/0.00
  execution time (avg/stddev): 36.6477/0.00

```

Figure 34 3<sup>rd</sup> execution

```

33435571CPU speed:
  events per second: 834971.94

General statistics:
  total time:          40.0002s
  total number of events: 33400301

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                0.44
  95th percentile:    0.00
  sum:                36663.06

Threads fairness:
  events (avg/stddev): 33400301.0000/0.00
  execution time (avg/stddev): 36.6631/0.00

```

Figure 35 4<sup>th</sup> execution

```

CPU speed:
  events per second: 838175.39

General statistics:
  total time:          40.0002s
  total number of events: 33528495

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                1.18
  95th percentile:   0.00
  sum:                36658.90

Threads fairness:
  events (avg/stddev): 33528495.0000/0.00
  execution time (avg/stddev): 36.6589/0.00

```

Figure 36 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Events/sec</b>	845823.89	829241.50	835851.67	834971.94	838175.39
<b>Total # of events</b>	33834363	33170874	33435571	33400301	33528495
<b>Min latency (ms)</b>	0.00	0.00	0.00	0.00	0.01
<b>Avg latency (ms)</b>	0.00	0.00	0.00	0.00	0.01
<b>Max latency (ms)</b>	3.88	7.94	1.71	0.44	1.18
<b>Execution time (s)</b>	36.6561	36.6315	36.6477	36.6631	36.6589

	Min	Max	Mean	Variance
<b>Events/sec</b>	829241.5	845823.89	836812.878	28938702.9
<b>Total # of events</b>	33170874	33834363	33473920.8	4.6325E+10
<b>Min latency (ms)</b>	0	0.01	0.002	0.000016
<b>Avg latency (ms)</b>	0	0.01	0.002	0.000016
<b>Max latency (ms)</b>	0.44	7.94	3.03	7.34072
<b>Execution time (s)</b>	36.6315	36.6631	36.65146	0.00012498

## Test case 2: Multi-threaded CPU performance test

Object: test out CPU performance with multiple threads.

The shell script that I created for this scenario:

```
#!/bin/sh

sysbench cpu --cpu-max-prime=100 --time=40 --threads=4 run
```

Figure 37 shell script

After test, the maximum prime number is set to 100, and the time limit is set to 40, the number of threads is 4. In this case, there will be more time spent on doing I/O, so the execution time will be smaller than the time limit.

**a. Results for executing five times in QEMU Ubuntu:**

```
CPU speed:
  events per second: 146939.77

General statistics:
  total time:          40.0009s
  total number of events: 5877904

Latency (ms):
  min:                 0.01
  avg:                 0.02
  max:                 25.28
  95th percentile:    0.01
  sum:                136262.54

Threads fairness:
  events (avg/stddev): 1469476.0000/25542.73
  execution time (avg/stddev): 34.0656/0.63

CPU speed:
  events per second: 147274.03

General statistics:
  total time:          40.0010s
  total number of events: 5891368

Latency (ms):
  min:                 0.01
  avg:                 0.02
  max:                 24.93
  95th percentile:    0.01
  sum:                136451.59

Threads fairness:
  events (avg/stddev): 1472842.0000/2256.04
  execution time (avg/stddev): 34.1129/0.15
```

Figure 38 1<sup>st</sup> execution

Figure 39 2<sup>nd</sup> execution

```
CPU speed:
  events per second: 145064.70

General statistics:
  total time:          40.0023s
  total number of events: 5803208

Latency (ms):
  min:                 0.01
  avg:                 0.02
  max:                 24.66
  95th percentile:    0.01
  sum:                136631.31

Threads fairness:
  events (avg/stddev): 1450802.0000/1817.03
  execution time (avg/stddev): 34.1578/0.22
```

Figure 40 3<sup>rd</sup> execution

```
CPU speed:
  events per second: 146949.55

General statistics:
  total time:          40.0024s
  total number of events: 5878560

Latency (ms):
  min:                 0.01
  avg:                 0.02
  max:                 45.06
  95th percentile:    0.01
  sum:                137079.56

Threads fairness:
  events (avg/stddev): 1469640.0000/1308.27
  execution time (avg/stddev): 34.2699/0.15
```

Figure 41 4<sup>th</sup> execution

```

CPU speed:
  events per second: 148115.62

General statistics:
  total time:          40.0010s
  total number of events: 5924959

Latency (ms):
  min:                0.01
  avg:                0.02
  max:                24.70
  95th percentile:   0.01
  sum:                136736.81

Threads fairness:
  events (avg/stddev): 1481239.7500/2350.34
  execution time (avg/stddev): 34.1842/0.07

```

Figure 42 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Events/sec</b>	146939.77	147274.03	145064.70	146949.55	148115.62
<b>Total # of events</b>	5877904	5891368	5803208	5878560	5924959
<b>Min latency (ms)</b>	0.01	0.01	0.01	0.01	0.01
<b>Avg latency (ms)</b>	0.02	0.02	0.02	0.02	0.02
<b>Max latency (ms)</b>	25.28	24.93	24.66	45.06	24.70
<b>Execution time (s)</b>	34.0656	34.1129	34.1578	34.2699	34.1842

	Min	Max	Mean	Variance
<b>Events/sec</b>	145064.7	148115.62	146868.734	997021.111
<b>Total # of events</b>	5803208	5924959	5875199.8	1587762317
<b>Min latency (ms)</b>	0.01	0.01	0.01	0
<b>Avg latency (ms)</b>	0.02	0.02	0.02	0
<b>Max latency (ms)</b>	24.66	45.06	28.926	65.125024
<b>Execution time (s)</b>	34.0656	34.2699	34.15808	0.00475597

*b. Results for executing five times in QEMU Ubuntu:*

```

CPU speed:
  events per second: 3026143.17

General statistics:
  total time:          40.0002s
  total number of events: 121054673

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                17.99
  95th percentile:   0.00
  sum:                143921.39

Threads fairness:
  events (avg/stddev): 30263668.2500/34108.98
  execution time (avg/stddev): 35.9803/0.04
CPU speed:
  events per second: 2950456.53

General statistics:
  total time:          40.0002s
  total number of events: 118023084

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                10.83
  95th percentile:   0.00
  sum:                144105.97

Threads fairness:
  events (avg/stddev): 29505771.0000/45429.87
  execution time (avg/stddev): 36.0265/0.04

```

Figure 43 1<sup>st</sup> execution

Figure 44 2<sup>nd</sup> execution

```

CPU speed:
  events per second: 2908579.13

General statistics:
  total time:          40.0002s
  total number of events: 116348784

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                12.23
  95th percentile:   0.00
  sum:                144050.57

Threads fairness:
  events (avg/stddev): 29087196.0000/46035.36
  execution time (avg/stddev): 36.0126/0.05

```

Figure 45 3<sup>rd</sup> execution

```

CPU speed:
  events per second: 2946680.76

General statistics:
  total time:          40.0002s
  total number of events: 117872248

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                8.20
  95th percentile:   0.00
  sum:                143977.69

Threads fairness:
  events (avg/stddev): 29468062.0000/38724.90
  execution time (avg/stddev): 35.9944/0.04

```

Figure 46 4<sup>th</sup> execution

```

CPU speed:
  events per second: 2967409.83

General statistics:
  total time:          40.0002s
  total number of events: 118701388

Latency (ms):
  min:                0.00
  avg:                0.00
  max:                4.14
  95th percentile:   0.00
  sum:                144059.86

Threads fairness:
  events (avg/stddev): 29675347.0000/44715.79
  execution time (avg/stddev): 36.0150/0.04

```

Figure 47 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
------	-----------------	-----------------	-----------------	-----------------	-----------------

<b>Events/sec</b>	3026143.17	2950456.53	2908579.13	2946680.76	2967409.83
<b>Total # of events</b>	121054673	118023084	116348784	117872248	118701388
<b>Min latency (ms)</b>	0.00	0.00	0.00	0.00	0.00
<b>Avg latency (ms)</b>	0.00	0.00	0.00	0.00	0.00
<b>Max latency (ms)</b>	17.99	10.83	12.23	8.20	4.14
<b>Execution time (s)</b>	35.9803	36.0265	36.0126	35.9944	36.0150

	Min	Max	Mean	Variance
<b>Events/sec</b>	2908579.13	3026143.17	2959853.88	1468460723
<b>Total # of events</b>	116348784	121054673	118400035	2.3532E+12
<b>Min latency (ms)</b>	0	0	0	0
<b>Avg latency (ms)</b>	0	0	0	0
<b>Max latency (ms)</b>	4.14	17.99	10.678	20.956616
<b>Execution time (s)</b>	35.9803	36.0265	36.00576	0.00026791

### Test case 3: Single threaded CPU performance test (large max prime number)

Object: test out CPU performance with single thread and large max prime number.

The shell script that I created for this scenario:

```
#!/bin/sh
sysbench cpu --cpu-max-prime=20000_--time=35 run
```

Figure 48 shell script

The max prime number is set to 20000, and time limit is set to 35. In this case, since the maximum prime number is very large, there will be more time spent on CPU's calculation and less time spent on doing I/O, so the execution time is very close to the time limit.

*a. Results for executing five times in QEMU Ubuntu:*



```

CPU speed:
  events per second: 164.11

General statistics:
  total time:          35.0048s
  total number of events: 5745

Latency (ms):
  min: 5.61
  avg: 6.08
  max: 13.79
  95th percentile: 6.79
  sum: 34951.90

Threads fairness:
  events (avg/stddev): 5745.0000/0.00
  execution time (avg/stddev): 34.9519/0.00

```

Figure 49 1<sup>st</sup> execution

```

CPU speed:
  events per second: 166.59

General statistics:
  total time:          35.0054s
  total number of events: 5832

Latency (ms):
  min: 5.61
  avg: 6.00
  max: 15.00
  95th percentile: 6.67
  sum: 34965.26

Threads fairness:
  events (avg/stddev): 5832.0000/0.00
  execution time (avg/stddev): 34.9653/0.00

```

Figure 50 2<sup>nd</sup> execution

```

CPU speed:
  events per second: 165.87

General statistics:
  total time:          35.0059s
  total number of events: 5807

Latency (ms):
  min: 5.61
  avg: 6.02
  max: 12.57
  95th percentile: 6.79
  sum: 34963.43

Threads fairness:
  events (avg/stddev): 5807.0000/0.00
  execution time (avg/stddev): 34.9634/0.00

```

Figure 51 3<sup>rd</sup> execution

```

CPU speed:
  events per second: 165.15

General statistics:
  total time:          35.0019s
  total number of events: 5781

Latency (ms):
  min: 5.61
  avg: 6.05
  max: 10.69
  95th percentile: 6.79
  sum: 34949.15

Threads fairness:
  events (avg/stddev): 5781.0000/0.00
  execution time (avg/stddev): 34.9491/0.00

```

Figure 52 4<sup>th</sup> execution

```

CPU speed:
  events per second: 163.71

General statistics:
  total time:          35.0040s
  total number of events: 5731

Latency (ms):
  min: 5.61
  avg: 6.10
  max: 18.54
  95th percentile: 6.79
  sum: 34950.18

Threads fairness:
  events (avg/stddev): 5731.0000/0.00
  execution time (avg/stddev): 34.9502/0.00

```

Figure 53 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Events/sec</b>	164.11	166.59	165.87	165.15	163.71
<b>Total # of events</b>	5745	5832	5807	5781	5731
<b>Min latency (ms)</b>	5.61	5.61	5.61	5.61	5.61
<b>Avg latency (ms)</b>	6.08	6.00	6.02	6.05	6.10
<b>Max latency (ms)</b>	13.79	15.00	12.57	10.69	18.54
<b>Execution time (s)</b>	35.0048	35.0054	35.0059	35.0019	35.0040

	Min	Max	Mean	Variance
<b>Events/sec</b>	163.71	166.59	165.086	1.145344

Total # of events	5731	5832	5779.2	1411.36
Min latency (ms)	5.61	5.61	5.61	0
Avg latency (ms)	6	6.1	6.05	0.00136
Max latency (ms)	10.69	18.54	14.118	6.917416
Execution time (s)	35.0019	35.0059	35.0044	1.964E-06

*b. Results for executing five times in QEMU Ubuntu:*

```

CPU speed:
  events per second: 526.73

General statistics:
  total time: 35.0015s
  total number of events: 18437

Latency (ms):
  min: 1.80
  avg: 1.90
  max: 3.85
  95th percentile: 2.11
  sum: 34989.58

Threads fairness:
  events (avg/stddev): 18437.0000/0.00
  execution time (avg/stddev): 34.9896/0.00

```

Figure 54 1<sup>st</sup> execution

```

CPU speed:
  events per second: 502.01

General statistics:
  total time: 35.0016s
  total number of events: 17572

Latency (ms):
  min: 1.80
  avg: 1.99
  max: 21.94
  95th percentile: 2.43
  sum: 34979.59

Threads fairness:
  events (avg/stddev): 17572.0000/0.00
  execution time (avg/stddev): 34.9796/0.00

```

Figure 55 2<sup>nd</sup> execution

```

CPU speed:
  events per second: 507.91

General statistics:
  total time: 35.0004s
  total number of events: 17778

Latency (ms):
  min: 1.80
  avg: 1.97
  max: 6.26
  95th percentile: 2.39
  sum: 34986.04

Threads fairness:
  events (avg/stddev): 17778.0000/0.00
  execution time (avg/stddev): 34.9860/0.00

```

Figure 56 3<sup>rd</sup> execution

```

CPU speed:
  events per second: 506.62

General statistics:
  total time: 35.0014s
  total number of events: 17733

Latency (ms):
  min: 1.80
  avg: 1.97
  max: 4.85
  95th percentile: 2.39
  sum: 34986.20

Threads fairness:
  events (avg/stddev): 17733.0000/0.00
  execution time (avg/stddev): 34.9862/0.00

```

Figure 57 4<sup>th</sup> execution

```

CPU speed:
  events per second: 509.46

General statistics:
  total time: 35.0002s
  total number of events: 17832

Latency (ms):
  min: 1.80
  avg: 1.96
  max: 3.77
  95th percentile: 2.39
  sum: 34985.73

Threads fairness:
  events (avg/stddev): 17832.0000/0.00
  execution time (avg/stddev): 34.9857/0.00

```

Figure 58 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Events/sec</b>	526.73	502.01	507.91	506.62	509.46
<b>Total # of events</b>	18437	17572	17778	17733	17832
<b>Min latency (ms)</b>	1.80	1.80	1.80	1.80	1.80
<b>Avg latency (ms)</b>	1.90	1.99	1.97	1.97	1.96
<b>Max latency (ms)</b>	3.85	21.94	6.26	4.85	3.77
<b>Execution time (s)</b>	34.9896	34.9796	34.9860	34.9862	34.9857

	Min	Max	Mean	Variance
<b>Events/sec</b>	502.01	526.73	510.546	71.665304
<b>Total # of events</b>	17572	18437	17870.4	87793.84
<b>Min latency (ms)</b>	1.8	1.8	1.8	0
<b>Avg latency (ms)</b>	1.9	1.99	1.958	0.000936
<b>Max latency (ms)</b>	3.77	21.94	8.134	48.459864
<b>Execution time (s)</b>	34.9796	34.9896	34.98542	1.0474E-05

#### Test case 4: Multi-threaded CPU performance test (large max prime number)

Object: test out CPU performance with multiple threads and large max prime number.

The shell script that I created for this scenario:

```

#!/bin/sh
sysbench cpu --cpu-max-prime=20000 --time=35 --threads=4 run

```

Figure 59 shell script

The max prime number is set to 20000, time limit is set to 35 and the number of threads is set to 4. In this case, since the maximum prime number is very large, there will be more time spent on CPU's calculation and less time spent on doing I/O, so the execution time is very close to the time limit.

**a. Results for executing five times in QEMU Ubuntu:**

```
CPU speed:
  events per second: 169.67

General statistics:
  total time:          35.0176s
  total number of events: 5942

Latency (ms):
  min:                 5.66
  avg:                 23.55
  max:                 45.92
  95th percentile:    34.33
  sum:                 139923.37

Threads fairness:
  events (avg/stddev): 1485.5000/1.80
  execution time (avg/stddev): 34.9808/0.01
```

Figure 60 1<sup>st</sup> execution

```
CPU speed:
  events per second: 162.36

General statistics:
  total time:          35.0121s
  total number of events: 5685

Latency (ms):
  min:                 5.66
  avg:                 24.59
  max:                 46.04
  95th percentile:    34.95
  sum:                 139784.91

Threads fairness:
  events (avg/stddev): 1421.2500/1.64
  execution time (avg/stddev): 34.9462/0.02
```

Figure 61 2<sup>nd</sup> execution

```
CPU speed:
  events per second: 164.30

General statistics:
  total time:          35.0128s
  total number of events: 5753

Latency (ms):
  min:                 5.71
  avg:                 24.30
  max:                 49.97
  95th percentile:    34.95
  sum:                 139786.93

Threads fairness:
  events (avg/stddev): 1438.2500/1.92
  execution time (avg/stddev): 34.9467/0.02
```

Figure 62 3<sup>rd</sup> execution

```
CPU speed:
  events per second: 161.90

General statistics:
  total time:          35.0172s
  total number of events: 5670

Latency (ms):
  min:                 5.73
  avg:                 24.64
  max:                 51.22
  95th percentile:    34.95
  sum:                 139726.66

Threads fairness:
  events (avg/stddev): 1417.5000/0.87
  execution time (avg/stddev): 34.9317/0.03
```

Figure 63 4<sup>th</sup> execution

```
CPU speed:
  events per second: 161.71

General statistics:
  total time:          35.0115s
  total number of events: 5662

Latency (ms):
  min:                 5.68
  avg:                 24.69
  max:                 45.30
  95th percentile:    34.95
  sum:                 139791.23

Threads fairness:
  events (avg/stddev): 1415.5000/1.50
  execution time (avg/stddev): 34.9478/0.02
```

Figure 64 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
Events/sec	169.67	162.36	164.30	161.90	161.71
Total # of events	5942	5685	5753	5670	5662
Min latency (ms)	5.66	5.66	5.71	5.73	5.68

<b>Avg latency (ms)</b>	23.55	24.59	24.30	24.64	24.69
<b>Max latency (ms)</b>	45.92	46.04	49.97	51.22	45.30
<b>Execution time (s)</b>	35.0176	35.0121	35.0128	35.0172	35.0115

	Min	Max	Mean	Variance
<b>Events/sec</b>	161.71	169.67	163.988	8.916376
<b>Total # of events</b>	5662	5942	5742.4	10990.64
<b>Min latency (ms)</b>	5.66	5.73	5.688	0.000776
<b>Avg latency (ms)</b>	23.55	24.69	24.354	0.179944
<b>Max latency (ms)</b>	45.3	51.22	47.69	5.84536
<b>Execution time (s)</b>	35.0115	35.0176	35.01424	6.8424E-06

*b. Results for executing five times in QEMU Ubuntu:*

```

CPU speed:
  events per second: 1877.81

General statistics:
  total time:          35.0019s
  total number of events: 65730

Latency (ms):
  min:                1.87
  avg:                2.13
  max:                20.33
  95th percentile:    2.61
  sum:                139959.35

Threads fairness:
  events (avg/stddev): 16432.5000/5.55
  execution time (avg/stddev): 34.9898/0.00

```

Figure 65 1<sup>st</sup> execution

```

CPU speed:
  events per second: 1822.12

General statistics:
  total time:          35.0016s
  total number of events: 63780

Latency (ms):
  min:                1.86
  avg:                2.19
  max:                12.19
  95th percentile:    2.71
  sum:                139951.37

Threads fairness:
  events (avg/stddev): 15945.0000/9.67
  execution time (avg/stddev): 34.9878/0.00

```

Figure 66 2<sup>nd</sup> execution

```

CPU speed:
  events per second: 1865.32

General statistics:
  total time:          35.0015s
  total number of events: 65292

Latency (ms):
  min:                1.87
  avg:                2.14
  max:                8.43
  95th percentile:    2.57
  sum:                139955.03

Threads fairness:
  events (avg/stddev): 16323.0000/6.78
  execution time (avg/stddev): 34.9888/0.00

```

Figure 67 3<sup>rd</sup> execution

```

CPU speed:
  events per second: 1872.39

General statistics:
  total time:          35.0019s
  total number of events: 65540

Latency (ms):
  min:                1.85
  avg:                2.14
  max:                14.33
  95th percentile:    2.52
  sum:                139960.30

Threads fairness:
  events (avg/stddev): 16385.0000/13.44
  execution time (avg/stddev): 34.9901/0.00

```

Figure 68 4<sup>th</sup> execution

```

CPU speed:
  events per second: 1873.87

General statistics:
  total time:          35.0020s
  total number of events: 65592

Latency (ms):
  min:                1.85
  avg:                2.13
  max:                5.41
  95th percentile:   2.61
  sum:                139959.77

Threads fairness:
  events (avg/stddev): 16398.0000/8.92
  execution time (avg/stddev): 34.9899/0.00

```

Figure 69 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Events/sec</b>	1877.81	1822.12	1865.32	1872.39	1873.87
<b>Total # of events</b>	65730	63780	65292	65540	65592
<b>Min latency (ms)</b>	1.87	1.86	1.87	1.85	1.85
<b>Avg latency (ms)</b>	2.13	2.19	2.14	2.14	2.13
<b>Max latency (ms)</b>	20.33	12.19	8.43	14.33	5.41
<b>Execution time (s)</b>	34.9898	34.9878	34.9888	34.9901	34.9899

	Min	Max	Mean	Variance
<b>Events/sec</b>	1822.12	1877.81	1862.302	419.957176
<b>Total # of events</b>	63780	65730	65186.8	514831.36
<b>Min latency (ms)</b>	1.85	1.87	1.86	8E-05
<b>Avg latency (ms)</b>	2.13	2.19	2.146	0.000504
<b>Max latency (ms)</b>	5.41	20.33	12.138	26.186336
<b>Execution time (s)</b>	34.9878	34.9901	34.98928	7.496E-07

## 7. Sysbench test under fileio mode

For this part of the experiment, I will conduct fileio performance test using sysbench in both QEMU Ubuntu and Docker Ubuntu. The experiment is conducted with 3 different testcases:

Multi-threaded fileio performance test with random read write.

Multi-threaded fileio performance test with sequential read.

Multi-threaded fileio performance test with sequential write.

## Test case 1: Multi-threaded fileio performance test with random read write.

Object: test out fileio performance with 4 threads under random read write mode.

The shell script that I created for this scenario:

```
#!/bin/sh
sysbench fileio --file-total-size=3G prepare
sysbench fileio --file-total-size=3G --file-test-mode=rndrw --time=40 --threads=4 run
sysbench fileio cleanup
```

Figure 70 shell script

### a. Results for executing five times in QEMU Ubuntu:

```
File operations:
  reads/s:          997.95
  writes/s:         665.30
  fsyncs/s:        2138.68

Throughput:
  read, MiB/s:      15.59
  written, MiB/s:   10.40

General statistics:
  total time:       40.1574s
  total number of events: 152171

Latency (ms):
  min:              0.01
  avg:              1.04
  max:              45.88
  95th percentile: 3.25
  sum:              157881.43

Threads fairness:
  events (avg/stddev): 38042.7500/146.11
  execution time (avg/stddev): 39.4704/0.01

sysbench 1.0.18 (using system LuaJIT 2.1.0-beta3)
```

Figure 71 1<sup>st</sup> execution

```
File operations:
  reads/s:          1022.52
  writes/s:         681.62
  fsyncs/s:        2192.60

Throughput:
  read, MiB/s:      15.98
  written, MiB/s:   10.65

General statistics:
  total time:       40.1040s
  total number of events: 155770

Latency (ms):
  min:              0.01
  avg:              1.01
  max:              82.26
  95th percentile: 3.19
  sum:              157854.50

Threads fairness:
  events (avg/stddev): 38942.5000/437.56
  execution time (avg/stddev): 39.4636/0.00
```

Figure 72 2<sup>nd</sup> execution

```
File operations:
  reads/s:          1019.57
  writes/s:         679.67
  fsyncs/s:        2185.50

Throughput:
  read, MiB/s:      15.93
  written, MiB/s:   10.62

General statistics:
  total time:       40.1328s
  total number of events: 155404

Latency (ms):
  min:              0.01
  avg:              1.02
  max:              97.12
  95th percentile: 3.13
  sum:              157860.95

Threads fairness:
  events (avg/stddev): 38851.0000/158.27
  execution time (avg/stddev): 39.4652/0.03
```

```
File operations:
  reads/s:          1024.97
  writes/s:         683.36
  fsyncs/s:        2197.32

Throughput:
  read, MiB/s:      16.02
  written, MiB/s:   10.68

General statistics:
  total time:       40.0953s
  total number of events: 156095

Latency (ms):
  min:              0.01
  avg:              1.01
  max:              84.33
  95th percentile: 3.19
  sum:              157832.72

Threads fairness:
  events (avg/stddev): 39023.7500/320.51
  execution time (avg/stddev): 39.4582/0.02
```

Figure 73 3<sup>rd</sup> executionFigure 74 4<sup>th</sup> execution

```

File operations:
  reads/s:          1017.87
  writes/s:         678.53
  fsyncs/s:        2183.27

Throughput:
  read, MiB/s:      15.90
  written, MiB/s:   10.60

General statistics:
  total time:       40.0990s
  total number of events: 155068

Latency (ms):
  min:              0.01
  avg:              1.02
  max:              48.14
  95th percentile: 3.19
  sum:              157722.40

Threads fairness:
  events (avg/stddev): 38767.0000/220.38
  execution time (avg/stddev): 39.4306/0.03

```

Figure 75 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Reads/sec</b>	997.95	1022.52	1019.57	1024.97	1017.87
<b>Writes/sec</b>	665.30	681.62	679.67	683.36	678.53
<b>Fsyncs/sec</b>	2138.68	2192.60	2185.50	2197.32	2183.27
<b>Throughput (r)</b>	15.59	15.98	15.93	16.02	15.90
<b>Throughput (w)</b>	10.40	10.65	10.62	10.68	10.60
<b>Total # of events</b>	152171	155770	155404	156095	155068
<b>Min latency (ms)</b>	0.01	0.01	0.01	0.01	0.01
<b>Avg latency (ms)</b>	1.04	1.01	1.02	1.01	1.02
<b>Max latency (ms)</b>	45.88	82.26	97.12	84.33	48.14
<b>Execution time (s)</b>	39.4704	39.4636	39.4652	39.4582	39.4306

	Min	Max	Mean	Variance
<b>Reads/sec</b>	997.95	1024.97	1016.576	92.671344
<b>Writes/sec</b>	665.3	683.36	677.696	41.146344
<b>Fsyncs/sec</b>	2138.68	2197.32	2179.474	441.128864
<b>Throughput (r)</b>	15.59	16.02	15.884	0.023304
<b>Throughput (w)</b>	10.4	10.68	10.59	0.00976
<b>Total # of events</b>	152171	156095	154901.6	1982918.64



Min latency (ms)	0.01	0.01	0.01	0
Avg latency (ms)	1.01	1.04	1.02	0.00012
Max latency (ms)	45.88	97.12	71.546	427.766864
Execution time (s)	39.4306	39.4704	39.4576	0.00019739

*b. Results for executing five times in Docker Ubuntu:*

```
File operations:
  reads/s:          5492.82
  writes/s:         3661.84
  fsyncs/s:         11730.61

Throughput:
  read, MiB/s:       85.83
  written, MiB/s:     57.22

General statistics:
  total time:         40.0220s
  total number of events: 835386

Latency (ms):
  min:                0.00
  avg:                0.19
  max:                882.55
  95th percentile:    0.51
  sum:               159468.65

Threads fairness:
  events (avg/stddev): 208846.5000/1831.05
  execution time (avg/stddev): 39.8672/0.00
```

Figure 76 1<sup>st</sup> execution

```
File operations:
  reads/s:          5554.13
  writes/s:         3702.71
  fsyncs/s:         11859.55

Throughput:
  read, MiB/s:       86.78
  written, MiB/s:     57.85

General statistics:
  total time:         40.0232s
  total number of events: 844660

Latency (ms):
  min:                0.00
  avg:                0.19
  max:                187.57
  95th percentile:    0.51
  sum:               159469.67

Threads fairness:
  events (avg/stddev): 211165.0000/959.45
  execution time (avg/stddev): 39.8674/0.00
```

Figure 77 2<sup>nd</sup> execution

```
File operations:
  reads/s:          5103.99
  writes/s:         3402.62
  fsyncs/s:         10898.43

Throughput:
  read, MiB/s:       79.75
  written, MiB/s:     53.17

General statistics:
  total time:         40.0264s
  total number of events: 776227

Latency (ms):
  min:                0.00
  avg:                0.21
  max:                815.97
  95th percentile:    0.51
  sum:               159467.78

Threads fairness:
  events (avg/stddev): 194056.7500/1455.62
  execution time (avg/stddev): 39.8669/0.00
```

Figure 78 3<sup>rd</sup> execution

```
File operations:
  reads/s:          5484.48
  writes/s:         3656.28
  fsyncs/s:         11711.18

Throughput:
  read, MiB/s:       85.69
  written, MiB/s:     57.13

General statistics:
  total time:         40.0282s
  total number of events: 834181

Latency (ms):
  min:                0.00
  avg:                0.19
  max:                172.40
  95th percentile:    0.51
  sum:               159458.92

Threads fairness:
  events (avg/stddev): 208545.2500/575.01
  execution time (avg/stddev): 39.8647/0.00
```

Figure 79 4<sup>th</sup> execution

```

File operations:
  reads/s:          5468.45
  writes/s:         3645.59
  fsyncs/s:        11677.07

Throughput:
  read, MiB/s:      85.44
  written, MiB/s:   56.96

General statistics:
  total time:        40.0249s
  total number of events: 831676

Latency (ms):
  min:              0.00
  avg:              0.19
  max:              147.27
  95th percentile: 0.52
  sum:              159445.82

Threads fairness:
  events (avg/stddev): 207919.0000/599.76
  execution time (avg/stddev): 39.8615/0.01

```

Figure 80 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Reads/sec</b>	5492.82	5554.13	5103.99	5484.48	5468.45
<b>Writes/sec</b>	3661.84	3702.71	3402.62	3656.28	3645.59
<b>Fsyncs/sec</b>	11730.61	11859.55	10898.43	11711.18	11677.07
<b>Throughput (r)</b>	85.83	86.78	79.75	85.69	85.44
<b>Throughput (w)</b>	57.22	57.85	53.17	57.13	56.96
<b>Total # of events</b>	835386	844660	776227	834181	831676
<b>Min latency (ms)</b>	0.00	0.00	0.00	0.00	0.00
<b>Avg latency (ms)</b>	0.19	0.19	0.21	0.19	0.19
<b>Max latency (ms)</b>	882.55	187.57	815.97	172.40	147.27
<b>Execution time (s)</b>	39.8672	39.8674	39.8669	39.8647	39.8615

	Min	Max	Mean	Variance
<b>Reads/sec</b>	5103.99	5554.13	5420.774	25931.6014
<b>Writes/sec</b>	3402.62	3702.71	3613.808	11524.9953
<b>Fsyncs/sec</b>	10898.43	11859.55	11575.368	118378.548
<b>Throughput (r)</b>	79.75	86.78	84.698	6.326696
<b>Throughput (w)</b>	53.17	57.85	56.466	2.806504
<b>Total # of events</b>	776227	844660	824426	600080496
<b>Min latency (ms)</b>	0	0	0	0
<b>Avg latency (ms)</b>	0.19	0.21	0.194	6.4E-05

<b>Max latency (ms)</b>	147.27	882.55	441.152	111643.765
<b>Execution time (s)</b>	39.8615	39.8674	39.86554	5.0184E-06

## Test case 2: Multi-threaded fileio performance test with sequential read.

Object: test out fileio performance with 4 threads under sequential read mode.

The shell script that I created for this scenario:

```

QEMU
#!/bin/sh
sysbench fileio --file-total-size=3G prepare
sysbench fileio --file-total-size=3G --file-test-mode=seqrd --time=40 --threads=4 run
sysbench fileio cleanup

```

Figure 81 shell script

### a. Results for executing five times in QEMU Ubuntu:

```

File operations:
  reads/s:          11132.85
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      173.95
  written, MiB/s:    0.00

General statistics:
  total time:        40.0032s
  total number of events: 445373

Latency (ms):
  min:              0.01
  avg:              0.33
  max:              95.43
  95th percentile: 0.40
  sum:              147277.01

Threads fairness:
  events (avg/stddev): 111343.2500/316.76
  execution time (avg/stddev): 36.8193/0.22

```

Figure 82 1<sup>st</sup> execution

```

File operations:
  reads/s:          11764.69
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      183.82
  written, MiB/s:    0.00

General statistics:
  total time:        40.0091s
  total number of events: 470716

Latency (ms):
  min:              0.01
  avg:              0.31
  max:              55.99
  95th percentile: 0.38
  sum:              146554.36

Threads fairness:
  events (avg/stddev): 117679.0000/211.21
  execution time (avg/stddev): 36.6386/0.18

```

Figure 83 2<sup>nd</sup> execution

```

File operations:
  reads/s:          11067.71
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      172.93
  written, MiB/s:    0.00

General statistics:
  total time:        40.0182s
  total number of events: 442939

Latency (ms):
  min:               0.01
  avg:               0.33
  max:               109.70
  95th percentile:  0.42
  sum:               146392.20

Threads fairness:
  events (avg/stddev): 110734.7500/429.41
  execution time (avg/stddev): 36.5980/0.15

```

Figure 84 3<sup>rd</sup> execution

```

File operations:
  reads/s:          11280.36
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      176.26
  written, MiB/s:    0.00

General statistics:
  total time:        40.0061s
  total number of events: 451319

Latency (ms):
  min:               0.01
  avg:               0.33
  max:               75.35
  95th percentile:  0.42
  sum:               147019.51

Threads fairness:
  events (avg/stddev): 112829.7500/339.86
  execution time (avg/stddev): 36.7549/0.13

```

Figure 85 4<sup>th</sup> execution

```

File operations:
  reads/s:          11225.59
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      175.40
  written, MiB/s:    0.00

General statistics:
  total time:        40.0077s
  total number of events: 449143

Latency (ms):
  min:               0.01
  avg:               0.33
  max:               55.12
  95th percentile:  0.42
  sum:               146326.98

Threads fairness:
  events (avg/stddev): 112285.7500/217.94
  execution time (avg/stddev): 36.5817/0.14

```

Figure 86 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Reads/sec</b>	11132.85	11764.69	11067.71	11280.36	11225.59
<b>Throughput (r)</b>	173.95	183.82	172.93	176.26	175.40
<b>Total # of events</b>	445373	470716	442939	451319	449143
<b>Min latency (ms)</b>	0.01	0.01	0.01	0.01	0.01
<b>Avg latency (ms)</b>	0.33	0.31	0.33	1.33	0.33
<b>Max latency (ms)</b>	95.43	55.99	109.70	75.35	55.12
<b>Execution time (s)</b>	36.8193	36.6386	36.5980	36.7549	36.5817

	Min	Max	Mean	Variance
<b>Reads/sec</b>	11067.71	11764.69	11294.24	60718.2505

Throughput (r)	172.93	183.82	176.472	14.818696
Total # of events	442939	470716	451898	96976339.2
Min latency (ms)	0.01	0.01	0.01	0
Avg latency (ms)	0.31	1.33	0.526	0.161664
Max latency (ms)	55.12	109.7	78.318	464.629256
Execution time (s)	36.5817	36.8193	36.6785	0.00862082

*b. Results for executing five times in Docker Ubuntu:*

```
File operations:
  reads/s:          793346.70
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      12396.04
  written, MiB/s:    0.00

General statistics:
  total time:        40.0043s
  total number of events: 31739299

Latency (ms):
  min:               0.00
  avg:               0.00
  max:               1002.89
  95th percentile:  0.01
  sum:               143212.54

Threads fairness:
  events (avg/stddev): 7934824.7500/395114.04
  execution time (avg/stddev): 35.8031/0.32
```

Figure 87 1<sup>st</sup> execution

```
File operations:
  reads/s:          813338.97
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      12708.42
  written, MiB/s:    0.00

General statistics:
  total time:        40.0034s
  total number of events: 32537849

Latency (ms):
  min:               0.00
  avg:               0.00
  max:               685.00
  95th percentile:  0.00
  sum:               144194.06

Threads fairness:
  events (avg/stddev): 8134462.2500/331562.46
  execution time (avg/stddev): 36.0485/0.76
```

Figure 88 2<sup>nd</sup> execution

```
File operations:
  reads/s:          734416.70
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      11475.26
  written, MiB/s:    0.00

General statistics:
  total time:        40.0135s
  total number of events: 29388249

Latency (ms):
  min:               0.00
  avg:               0.00
  max:               1001.34
  95th percentile:  0.00
  sum:               146734.95

Threads fairness:
  events (avg/stddev): 7347062.2500/224794.56
  execution time (avg/stddev): 36.6837/0.10
```

```
File operations:
  reads/s:          870657.53
  writes/s:         0.00
  fsyncs/s:         0.00

Throughput:
  read, MiB/s:      13604.02
  written, MiB/s:    0.00

General statistics:
  total time:        40.0028s
  total number of events: 34830422

Latency (ms):
  min:               0.00
  avg:               0.00
  max:               565.92
  95th percentile:  0.01
  sum:               143409.38

Threads fairness:
  events (avg/stddev): 8707605.5000/165956.65
  execution time (avg/stddev): 35.8523/0.33
```

Figure 89 3<sup>rd</sup> executionFigure 90 4<sup>th</sup> execution

```

File operations:
  reads/s:                818622.04
  writes/s:               0.00
  fsyncs/s:               0.00

Throughput:
  read, MiB/s:            12790.97
  written, MiB/s:         0.00

General statistics:
  total time:              40.0001s
  total number of events:  32746526

Latency (ms):
  min:                     0.00
  avg:                     0.00
  max:                     1005.79
  95th percentile:        0.01
  sum:                    141631.39

Threads fairness:
  events (avg/stddev):     8186631.5000/1025259.31
  execution time (avg/stddev): 35.4078/1.17

```

Figure 91 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Reads/sec</b>	793346.70	813338.97	734416.70	870657.53	818622.04
<b>Throughput (r)</b>	12396.04	12708.42	11475.26	13604.02	12790.97
<b>Total # of events</b>	31739299	32537849	29388249	34830422	32746526
<b>Min latency (ms)</b>	0.00	0.00	0.00	0.00	0.00
<b>Avg latency (ms)</b>	0.00	0.00	0.00	0.00	0.00
<b>Max latency (ms)</b>	1002.89	685.00	1001.34	565.92	1005.79
<b>Execution time (s)</b>	35.8031	36.0485	36.6837	35.8523	35.4078

	Min	Max	Mean	Variance
<b>Reads/sec</b>	734416.7	870657.53	806076.388	1935603645
<b>Throughput (r)</b>	11475.26	13604.02	12594.942	472558.486
<b>Total # of events</b>	29388249	34830422	32248469	3.0877E+12
<b>Min latency (ms)</b>	0	0	0	0
<b>Avg latency (ms)</b>	0	0	0	0
<b>Max latency (ms)</b>	565.92	1005.79	852.188	35690.4363

Execution time (s)	35.4078	36.6837	35.95908	0.17454229
--------------------	---------	---------	----------	------------

### Test case 3: Multi-threaded fileio performance test with sequential write.

Object: test out fileio performance with 4 threads under sequential write mode.

The shell script that I created for this scenario:

```
#!/bin/sh
sysbench fileio --file-total-size=3G prepare
sysbench fileio --file-total-size=3G --file-test-mode=seqwr --time=40 --threads=4 run
sysbench fileio cleanup
```

Figure 92 shell script

#### a. Results for executing five times in QEMU Ubuntu:

```
File operations:
  reads/s:          0.00
  writes/s:         2469.85
  fsyncs/s:         3172.68

Throughput:
  read, MiB/s:      0.00
  written, MiB/s:   38.59

General statistics:
  total time:       40.0818s
  total number of events: 225660

Latency (ms):
  min:              0.09
  avg:              0.70
  max:              136.72
  95th percentile: 3.25
  sum:              157002.35

Threads fairness:
  events (avg/stddev): 56415.0000/110.69
  execution time (avg/stddev): 39.2506/0.03
```

Figure 93 1<sup>st</sup> execution

```
File operations:
  reads/s:          0.00
  writes/s:         2521.54
  fsyncs/s:         3237.35

Throughput:
  read, MiB/s:      0.00
  written, MiB/s:   39.40

General statistics:
  total time:       40.0926s
  total number of events: 230388

Latency (ms):
  min:              0.09
  avg:              0.68
  max:              83.25
  95th percentile: 3.19
  sum:              157364.32

Threads fairness:
  events (avg/stddev): 57597.0000/565.01
  execution time (avg/stddev): 39.3411/0.06
```

Figure 94 2<sup>nd</sup> execution

```

File operations:
  reads/s:          0.00
  writes/s:         2507.26
  fsyncs/s:         3219.67

Throughput:
  read, MiB/s:      0.00
  written, MiB/s:    39.18

General statistics:
  total time:        40.0822s
  total number of events: 229044

Latency (ms):
  min:               0.09
  avg:               0.69
  max:               106.94
  95th percentile:  3.13
  sum:               157154.92

Threads fairness:
  events (avg/stddev): 57261.0000/549.52
  execution time (avg/stddev): 39.2887/0.06

```

Figure 95 3<sup>rd</sup> execution

```

File operations:
  reads/s:          0.00
  writes/s:         2552.60
  fsyncs/s:         3279.75

Throughput:
  read, MiB/s:      0.00
  written, MiB/s:    39.88

General statistics:
  total time:        40.0794s
  total number of events: 233255

Latency (ms):
  min:               0.09
  avg:               0.67
  max:               95.06
  95th percentile:  3.13
  sum:               157343.26

Threads fairness:
  events (avg/stddev): 58313.7500/556.38
  execution time (avg/stddev): 39.3358/0.05

```

Figure 96 4<sup>th</sup> execution

```

File operations:
  reads/s:          0.00
  writes/s:         2547.57
  fsyncs/s:         3273.60

Throughput:
  read, MiB/s:      0.00
  written, MiB/s:    39.81

General statistics:
  total time:        40.0765s
  total number of events: 232790

Latency (ms):
  min:               0.09
  avg:               0.68
  max:               79.38
  95th percentile:  3.07
  sum:               157275.98

Threads fairness:
  events (avg/stddev): 58197.5000/418.61
  execution time (avg/stddev): 39.3190/0.02

```

Figure 97 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
<b>Writes/sec</b>	2469.85	2521.54	2507.26	2552.60	2547.57
<b>Fsyncs/sec</b>	3172.68	3237.35	3219.67	3279.75	3273.60
<b>Throughput (w)</b>	38.59	39.40	39.18	39.88	39.81
<b>Total # of events</b>	225660	230388	229044	233255	232790
<b>Min latency (ms)</b>	0.09	0.09	0.09	0.09	0.09
<b>Avg latency (ms)</b>	0.70	0.68	0.69	0.67	0.68
<b>Max latency (ms)</b>	136.72	83.25	106.94	95.06	79.38
<b>Execution time (s)</b>	39.2506	39.3411	39.2887	39.3358	39.3190

	Min	Max	Mean	Variance
<b>Writes/sec</b>	2469.85	2552.6	2519.764	900.457624



<b>Fsyncs/sec</b>	3172.68	3279.75	3236.61	1520.77516
<b>Throughput (w)</b>	38.59	39.88	39.372	0.219816
<b>Total # of events</b>	225660	233255	230227.4	7604130.24
<b>Min latency (ms)</b>	0.09	0.09	0.09	2.3111E-34
<b>Avg latency (ms)</b>	0.67	0.7	0.684	0.000104
<b>Max latency (ms)</b>	79.38	136.72	100.27	425.2616
<b>Execution time (s)</b>	39.2506	39.3411	39.30704	0.00113042

***b. Results for executing five times in Docker Ubuntu:***

File operations:		File operations:	
reads/s:	0.00	reads/s:	0.00
writes/s:	9466.48	writes/s:	11060.52
fsyncs/s:	12129.58	fsyncs/s:	14169.13
Throughput:		Throughput:	
read, MiB/s:	0.00	read, MiB/s:	0.00
written, MiB/s:	147.91	written, MiB/s:	172.82
General statistics:		General statistics:	
total time:	40.0241s	total time:	40.0397s
total number of events:	863880	total number of events:	1009767
Latency (ms):		Latency (ms):	
min:	0.01	min:	0.01
avg:	0.18	avg:	0.16
max:	459.54	max:	88.31
95th percentile:	0.31	95th percentile:	0.29
sum:	159229.67	sum:	159187.49
Threads fairness:		Threads fairness:	
events (avg/stddev):	215970.0000/645.94	events (avg/stddev):	252441.7500/1471.30
execution time (avg/stddev):	39.8074/0.01	execution time (avg/stddev):	39.7969/0.00

Figure 98 1<sup>st</sup> execution

Figure 99 2<sup>nd</sup> execution

File operations:		File operations:	
reads/s:	0.00	reads/s:	0.00
writes/s:	10980.49	writes/s:	11257.47
fsyncs/s:	14065.10	fsyncs/s:	14419.57
Throughput:		Throughput:	
read, MiB/s:	0.00	read, MiB/s:	0.00
written, MiB/s:	171.57	written, MiB/s:	175.90
General statistics:		General statistics:	
total time:	40.0228s	total time:	40.0243s
total number of events:	1001917	total number of events:	1027227
Latency (ms):		Latency (ms):	
min:	0.01	min:	0.01
avg:	0.16	avg:	0.15
max:	210.67	max:	343.15
95th percentile:	0.28	95th percentile:	0.27
sum:	159192.37	sum:	159192.26
Threads fairness:		Threads fairness:	
events (avg/stddev):	250479.2500/933.82	events (avg/stddev):	256806.7500/710.69
execution time (avg/stddev):	39.7981/0.01	execution time (avg/stddev):	39.7981/0.01

Figure 100 3<sup>rd</sup> execution

Figure 101 4<sup>th</sup> execution

File operations:	
reads/s:	0.00
writes/s:	9832.96
fsyncs/s:	12597.46
Throughput:	
read, MiB/s:	0.00
written, MiB/s:	153.64
General statistics:	
total time:	40.0272s
total number of events:	897347
Latency (ms):	
min:	0.01
avg:	0.18
max:	296.44
95th percentile:	0.32
sum:	159188.26
Threads fairness:	
events (avg/stddev):	224336.7500/808.51
execution time (avg/stddev):	39.7971/0.01

Figure 102 5<sup>th</sup> execution

The results show in table:

Time	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>	4 <sup>th</sup>	5 <sup>th</sup>
Writes/sec	9466.48	11060.52	10980.49	11257.47	9832.96
Fsyncs/sec	12129.58	14169.13	14065.10	14419.57	12597.46
Throughput (w)	147.91	172.82	171.57	175.90	153.64
Total # of events	863880	1009767	1001917	1027227	897347
Min latency (ms)	0.01	0.01	0.01	0.01	0.01
Avg latency (ms)	0.18	0.16	0.16	0.15	0.18
Max latency (ms)	459.54	88.31	210.67	343.15	296.44
Execution time (s)	39.8074	39.7969	39.7981	39.7981	39.7971

	Min	Max	Mean	Variance
--	-----	-----	------	----------

<b>Writes/sec</b>	9466.48	11257.47	10519.584	526000.48
<b>Fsyncs/sec</b>	12129.58	14419.57	13476.168	860494.312
<b>Throughput (w)</b>	147.91	175.9	164.368	128.449576
<b>Total # of events</b>	863880	1027227	960027.6	4383541541
<b>Min latency (ms)</b>	0.01	0.01	0.01	0
<b>Avg latency (ms)</b>	0.15	0.18	0.166	0.000144
<b>Max latency (ms)</b>	88.31	459.54	279.622	15608.7597
<b>Execution time (s)</b>	39.7969	39.8074	39.79952	1.577E-05

## 8. Analysis

When doing CPU test, the CPU tends to do calculation much faster, and the execution time is low, when the maximum prime number is low. And when maximum prime number is high, the CPU shows a significant drop in calculation speed, and the execution time is very close to the running time. This is because when the prime number is high, the CPU will need to spend more time doing calculation, there will be less time spent on accessing memory, etc., which causes the execution time very close to the running time.

When using multiple threads to calculate, there will be a significant increase in latency.

When testing in Docker Ubuntu, the execution speed of CPU and file I/O speed tends to be larger than doing test in QEMU Ubuntu. Typically, three or more times larger.