# Multi-threaded word count

32214362 Yoonseo Cho

Free days remaining: 5 / Used: 0

# Contents

# Introduction

The last assignment, we dealt with process management(fork(), execve()). In this assignment, we are going to implement a N:M producer and consumer multi-threading program. The goal of the program is to read a text file with a series of producer threads, and write each separated line into a shared object. Then with consumer threads, generate statistics of the read input file.

# Concepts

Multi-threading is a technique that allows a single program to execute multiple threads concurrently. A thread is the smallest unit of a process. Unlike processes, which run in separate memory spaces, threads share the same memory space. But, to be more specific, there are types of memory regions (heap, static) that can be shared across multiple threads. This enables sharing data across threads more efficiently compared to that of processes. However, it is still required to coordinate (synchronize) each processes/threads for data consistency as well as avoiding deadlocks.

For implementation, we would be using the library pthread for the Linux environment. To be more specific, we will be using pthread_mutex as well as pthread_cond for sending conditions across multiple threads.

# Implementation

## Goal 1) Correct the given code to implement 1:1

First of all, I had to fix the primitive *prod_cons.c* code. When I executed the program, I used the LICENSE file as an input and setted up to create with 1 producer and 1 consumer. However, it didn't work because the program couldn't handle the input file properly.

```
● choyoonseo@joyunseoui-MacBookAir 2024-os-hw2 % ./a.out ./LICENSE 1 1
  main continuing
  Cons: 0 lines
  main: consumer_0 joined with 0
  Prod_6aef7000: 21 lines
  main: producer_0 joined with 21
```

**<Figure 1 - Failure of 1 producer 1 consumer>**

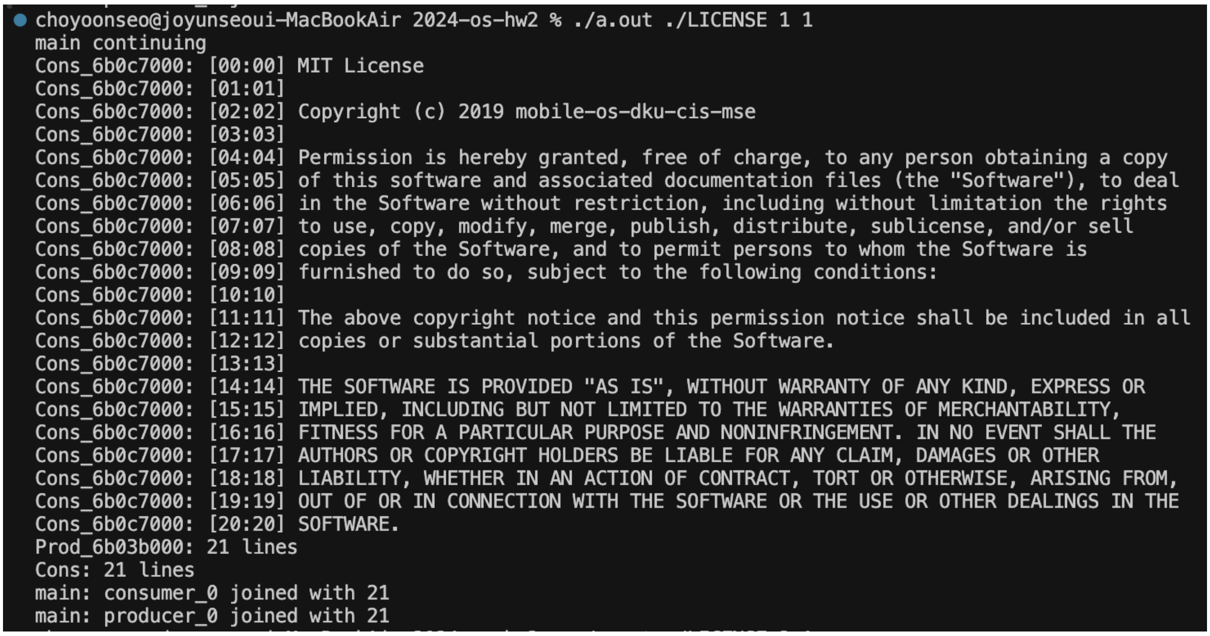
Due to a race condition between the single producer and consumer, I implemented a mutex lock to avoid it. In other words, I synchronized both threads.

Before entering the critical section, I used a mutex lock to guarantee mutual exclusion. `pthread_mutex_lock()` prevents other threads from entering the critical section. After locking the mutex, it is important to unlock it. `pthread_mutex_unlock()` allows other threads to enter the critical section. Without unlocking, other threads never get their turn, which can lead to deadlock.

Moreover, I used a condition variable because if I had only used a mutex, it would have been inevitable to experience busy waiting, which would waste CPU resources. `pthread_cond_wait()` makes the thread remain blocked until another thread signals the condition variable using `pthread_cond_signal()` or `pthread_cond_broadcast()`. `pthread_cond_signal()` sends a signal which wakes up the waiting thread so it can continue processing.

It is important to initialize them before using those mutex and condition variables. I used `pthread_mutex_init()` and `pthread_cond_init()`.

After using them, it is crucial to destroy them. `pthread_mutex_destroy()` and `pthread_cond_destroy()` inform the operating system that we've finished using the mutex or condition variable, and help clean up kernel resources.



```
choyoonseo@joyunseoui-MacBookAir 2024-os-hw2 % ./a.out ./LICENSE 1 1
main continuing
Cons_6b0c7000: [00:00] MIT License
Cons_6b0c7000: [01:01]
Cons_6b0c7000: [02:02] Copyright (c) 2019 mobile-os-dku-cis-mse
Cons_6b0c7000: [03:03]
Cons_6b0c7000: [04:04] Permission is hereby granted, free of charge, to any person obtaining a copy
Cons_6b0c7000: [05:05] of this software and associated documentation files (the "Software"), to deal
Cons_6b0c7000: [06:06] in the Software without restriction, including without limitation the rights
Cons_6b0c7000: [07:07] to use, copy, modify, merge, publish, distribute, sublicense, and/or sell
Cons_6b0c7000: [08:08] copies of the Software, and to permit persons to whom the Software is
Cons_6b0c7000: [09:09] furnished to do so, subject to the following conditions:
Cons_6b0c7000: [10:10]
Cons_6b0c7000: [11:11] The above copyright notice and this permission notice shall be included in all
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Cons_6b0c7000: [17:17] AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER
Cons_6b0c7000: [18:18] LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM,
Cons_6b0c7000: [19:19] OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE
Cons_6b0c7000: [20:20] SOFTWARE.
Prod_6b03b000: 21 lines
Cons: 21 lines
main: consumer_0 joined with 21
main: producer_0 joined with 21
```

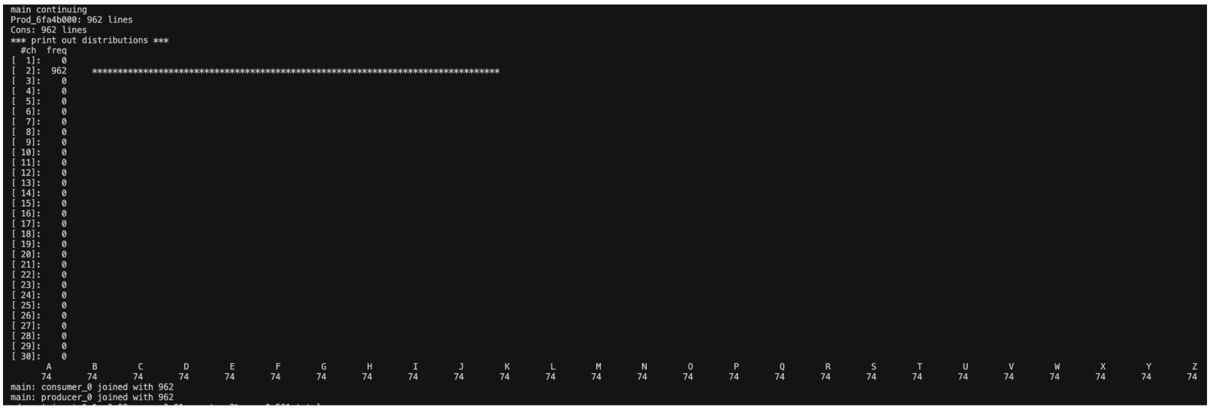
**<Figure 2 - Success of 1 producer 1 consumer>**

Finally, it works!

`Cons_6b037000` is the identifier of consumer thread, and `Pros_6b03b000` is the identifier of producer thread. `Cons_6b037000: [00:00] MIT License` displays the work done by the consumer thread. As I have set up 1 consumer, this consumer reads every single line from the input file. `Pros_6b03b000: 21 lines` indicates that the producer thread has completed its task, which is reading from the input file. `Cons: 21 lines` shows that the consumer thread has finished its work. `main: consumer_0 joined with 21` means that the main thread has completed synchronization with the consumer thread (consumer_0). `main: producer_0 joined with 21` means that the main thread has completed synchronization with the producer thread (producer_0).

# Goal 2) Add character statistics code

Now, let’s count words! I added code to analyze and generate statistics for the string from *char_stat.c* to the consumer function.




**<Figure 3 - Successful character statistics of 1 producer 1 consumer>**

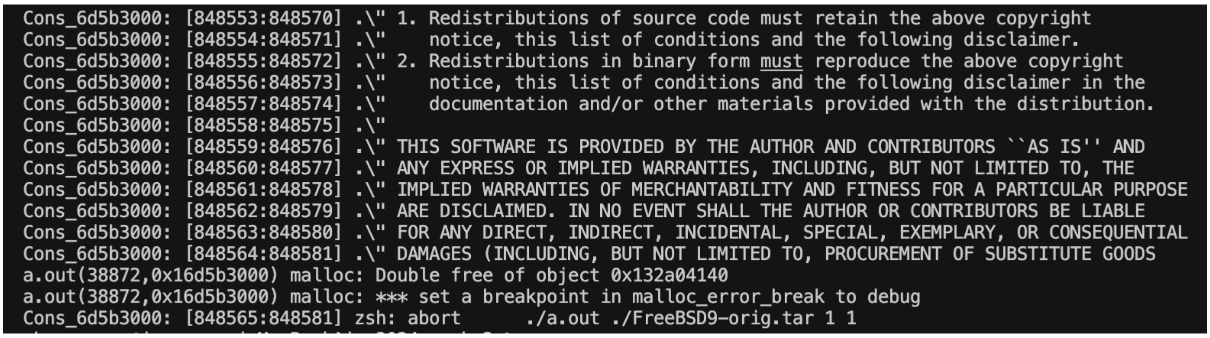
Yes it works!

To check the statistics, I created a simple input file that contains 74 instances of each letter of the alphabet.

# Goal 3) Use FreeBSD9-orig.tar as an input

Until now, I checked that the program works well with a simple file like README.md or LICENSE. From now on, I'm going to use a 600MB size of FreeBSD9-orig.tar file as an input.

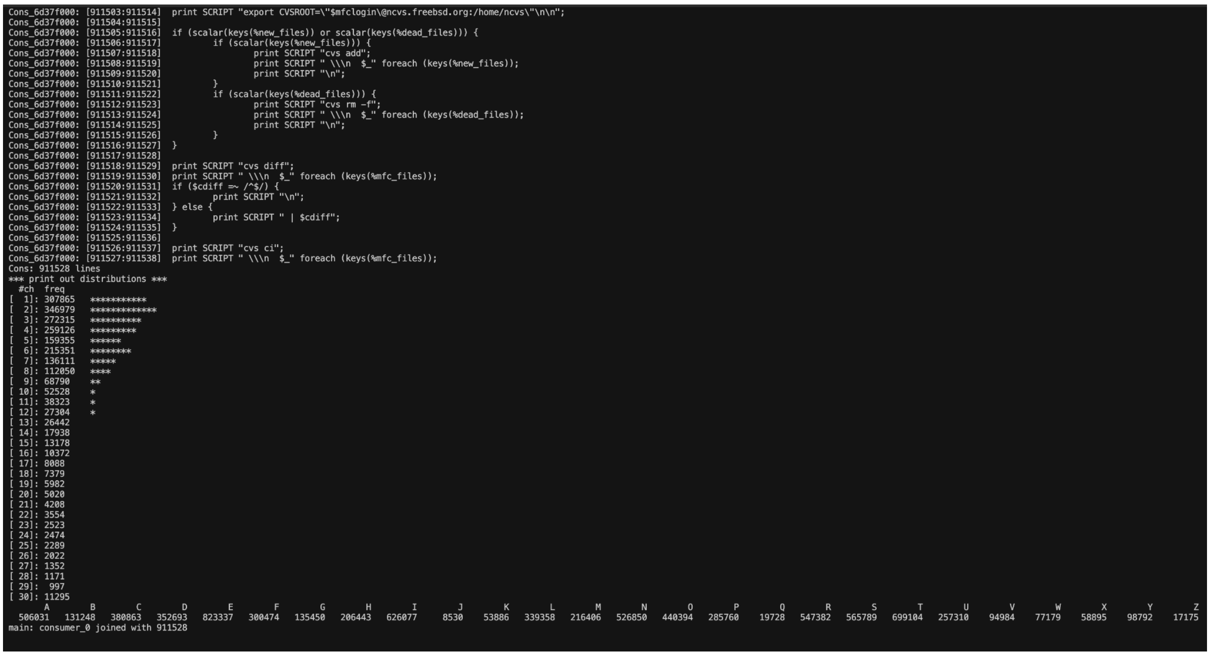
However, when I execute with the FreeBSD9-orig.tar file, the program stops due to the double free memory issue.



```
Cons_6d5b3000: [848553:848570] .\" 1. Redistributions of source code must retain the above copyright
Cons_6d5b3000: [848554:848571] .\"    notice, this list of conditions and the following disclaimer.
Cons_6d5b3000: [848555:848572] .\" 2. Redistributions in binary form must reproduce the above copyright
Cons_6d5b3000: [848556:848573] .\"    notice, this list of conditions and the following disclaimer in the
Cons_6d5b3000: [848557:848574] .\"    documentation and/or other materials provided with the distribution.
Cons_6d5b3000: [848558:848575] .\"
Cons_6d5b3000: [848559:848576] .\" THIS SOFTWARE IS PROVIDED BY THE AUTHOR AND CONTRIBUTORS ``AS IS'' AND
Cons_6d5b3000: [848560:848577] .\" ANY EXPRESS OR IMPLIED WARRANTIES, INCLUDING, BUT NOT LIMITED TO, THE
Cons_6d5b3000: [848561:848578] .\" IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE
Cons_6d5b3000: [848562:848579] .\" ARE DISCLAIMED. IN NO EVENT SHALL THE AUTHOR OR CONTRIBUTORS BE LIABLE
Cons_6d5b3000: [848563:848580] .\" FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL
Cons_6d5b3000: [848564:848581] .\" DAMAGES (INCLUDING, BUT NOT LIMITED TO, PROCUREMENT OF SUBSTITUTE GOODS
a.out(38872,0x16d5b3000) malloc: Double free of object 0x132a04140
a.out(38872,0x16d5b3000) malloc: *** set a breakpoint in malloc_error_break to debug
Cons_6d5b3000: [848565:848581] zsh: abort      ./a.out ./FreeBSD9-orig.tar 1 1
```

**<Figure 4 - Double free issue with FreeBSD9-orig.tar in 1 producer 1 consumer>**

It is due to the dangling pointer. To deal with this issue, I added `so-> line = NULL` after `free(so->line)` to prevent attempts to free memory that had already been freed. In other words, I set the pointer to NULL so that it no longer points to an invalid memory address.



**<Figure 5 - Deadlock issue with FreeBSD9-orig.tar in 1 producer 1 consumer>**

Right after solving the double free issue, a deadlock issue arose.

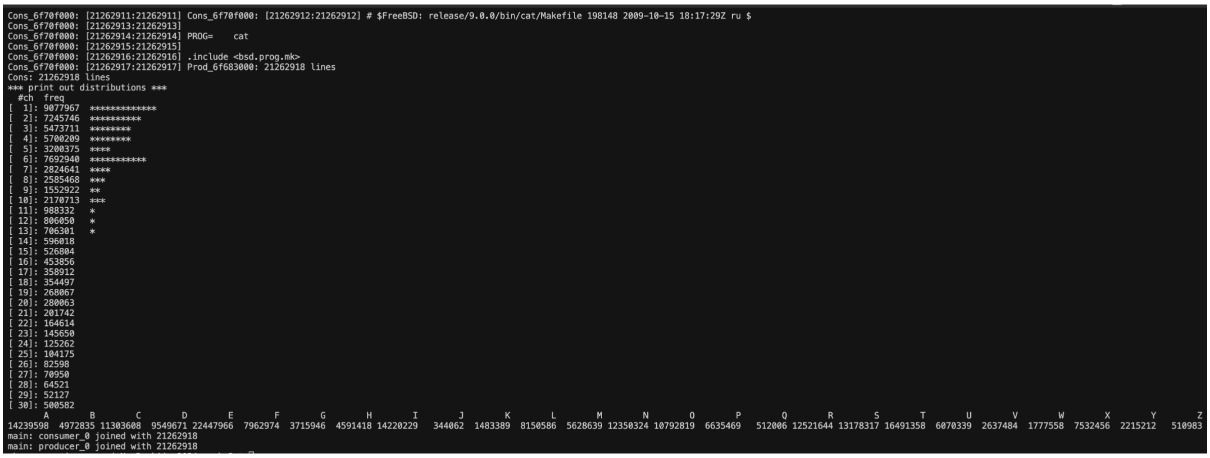
The program stopped after joining with the consumer thread. It seems like the producer thread cannot join with the main thread. It keeps waiting.

I thought it was interrupted by some other issue temporarily. So I forced the program to quit, and re-executed it 5 times. But every time I executed it, the total number of lines processed by the consumer thread was different.

So I asked ChatGPT why it is so.

It was because of a spurious wakeup.

From a software perspective, the code should execute normally, but the thread that should not wake up can wake up unexpectedly due to characteristics of the operating system or hardware. So I replaced the if statement with a while loop when I check whether the buffer is full or not in producer and consumer functions.




**<Figure 6 - Success with FreeBSD9-orig.tar in 1 producer 1 consumer>**

Finally it works!

Although it took more than 5 minutes to execute, it worked!


**<Figure 7 - Execution time with FreeBSD9-orig.tar in 1 producer 1 consumer>**

I used the `time` command to measure the execution time.

It took 70.16 seconds in user mode, which represents the actual program code execution time, and 198.04 seconds in system mode, which represents time spent on system calls like file I/O and memory management. The wall clock time, which is the total actual time taken from program start to finish was 6 minutes 43.85 seconds with a CPU utilization of 66%.

```
./a.out ./FreeBSD9-orig.tar 1 1  37.56s user 81.78s system 100% cpu 1:58.48 total
```

**<Figure 8 - Reduced time with FreeBSD9-orig.tar in 1 producer 1 consumer>**

It took so much time, so I changed the order of `pthread_mutex_unlock()` and `pthread_cond_signal()` to reduce context switching and decrease execution time. Also, I commented out unnecessary `printf()` statements.

As a result, the total execution time was reduced to ⅕ of the original time.

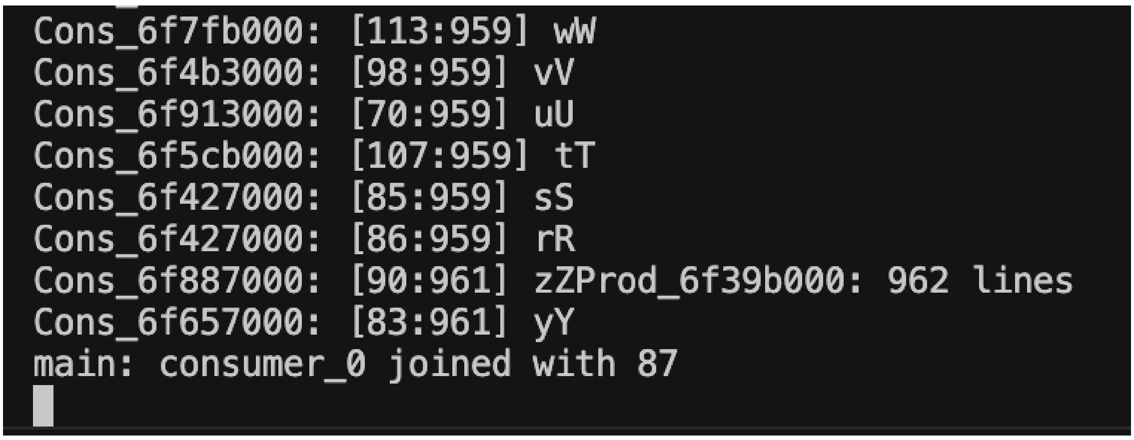
# Goal 4) Implement 1:N from 1:1

Let’s enhance the program so that it can execute with multiple consumers.

When handling 1 producer 1 consumer, the producer only reads a single line from the input file, and the shared object(buffer) can only hold a single line. However, when handling multiple consumers, the producer should read multiple lines from the input file and put them into the buffer.

So, I changed several things in the shared_object structure.

First, I changed a single pointer to a double pointer to store multiple strings. Second, I distinguished the condition variable like `thread_cond_t has_data` and `pthread_cond_t has_space` to better manage the buffer. Third, I used a `done` flag and a `count` variable instead of `full`, because the buffer contains multiple lines, not just a single line, and to clearly indicate whether the producer has finished reading the entire input file.



```
Cons_6f7fb000: [113:959] wW
Cons_6f4b3000: [98:959] vV
Cons_6f913000: [70:959] uU
Cons_6f5cb000: [107:959] tT
Cons_6f427000: [85:959] sS
Cons_6f427000: [86:959] rR
Cons_6f887000: [90:961] zZProd_6f39b000: 962 lines
Cons_6f657000: [83:961] yY
main: consumer_0 joined with 87
```

**<Figure 9 - Deadlock issue with input file in 1 producer 10 consumer>**

However, the deadlock issue occurred.

Some consumers might have been busy waiting because, before the producer finished, it only woke a single consumer using `pthread_cond_signal()` .

So I changed it to `pthread_cond_broadcast()` to wake up every consumer thread. Since a single consumer changed to multiple consumers, the producer needs to take care of all the threads.

```
Cons_6b8f3000: [81:953] rR
Cons_6b97f000: [109:954] sS
Cons_6b7db000: [101:961] zZProd_6b51f000: 962 lines
Cons_6b7db000: [102:961] yY
Cons_6b5ab000: [117:961] xX
Cons_6b867000: [92:961] wW
Cons_6b867000: [93:961] vV
Cons_6b6c3000: [80:961] uU
Cons_6b74f000: [91:961] tT
main: consumer_0 joined with 118
main: consumer_1 joined with 70
main: consumer_2 joined with 81
main: consumer_3 joined with 92
main: consumer_4 joined with 103
main: consumer_5 joined with 94
main: consumer_6 joined with 82
main: consumer_7 joined with 110
main: consumer_8 joined with 106
main: consumer_9 joined with 106
main: producer_0 joined with 962
./a.out ./input 1 10  0.00s user 0.04s system 87% cpu 0.048 total
```

**<Figure 10 - Race condition with input file in 1 producer 10 consumer>**

Now, the multi-threaded execution works well, but another issue occurred.

The problem was that the character statistics code exists within the consumer function. Since multiple consumers are running, the character statistics should be calculated after all of the consumer threads have completed.

Therefore, I moved the character statistics code into a separate function.

```
choyoonseo@joyunseoui-MacBookAir 2024-os-hw2 % ./a.out FreeBSD9-orig.tar 1 10
main continuing
Prod_6b8ef000: 21262918 lines
Cons_6bb1f000: 2127908 lines
Cons_6bc37000: 2111403 lines
Cons_6bbab000: 2140335 lines
Cons_6bcc3000: 2110018 lines
Cons_6b97b000: 2064722 lines
Cons_6bddb000: 2141987 lines
Cons_6ba07000: 2141253 lines
main: consumer_0 joined with 2064722
Cons_6be67000: 2155812 lines
main: consumer_1 joined with 2141253
Cons_6ba93000: 2136361 lines
Cons_6bd4f000: 2133119 lines
main: consumer_2 joined with 2136361
main: consumer_3 joined with 2127908
main: consumer_4 joined with 2140335
main: consumer_5 joined with 2111403
main: consumer_6 joined with 2110018
main: consumer_7 joined with 2133119
main: consumer_8 joined with 2141987
main: consumer_9 joined with 2155812
main: producer_0 joined with 21262918
*** print out distributions ***
  #ch  freq
[  1]: 9077967  *************
[  2]: 7245746  **********
[  3]: 5473711  ********
[  4]: 5700209  ********
[  5]: 3200375  ****
[  6]: 7692940  ***********
[  7]: 2824641  ****
[  8]: 2585468  ***
[  9]: 1552922  **
[ 10]: 2170713  ***
[ 11]: 988332   *
[ 12]: 806050   *
[ 13]: 706301   *
[ 14]: 596018
[ 15]: 526804
[ 16]: 453856
[ 17]: 358912
[ 18]: 354497
[ 19]: 268067
[ 20]: 280063
[ 21]: 201742
[ 22]: 164614
[ 23]: 145650
[ 24]: 125262
[ 25]: 104175
[ 26]: 82598
[ 27]: 70950
[ 28]: 64521
[ 29]: 52127
[ 30]: 500582
       A        B        C        D        E        F        G        H        I        J        K        L        M        N        O        P        Q        R        S        T        U        V        W        X        Y        Z
14239598  4972835 11303608  9549671 22447966  7962974  3715946  4591418 14220229   344062  1483389  8150586  5628639 12350324 10792819  6635469   512006 12521644 13178317 16491358  6070339  2637484  1777558  7532456  2215212   510983
```

**<Figure 11 - Success with FreeBSD9-orig.tar in 1 producer 10 consumer>**

Finally, it works!

As I used multiple consumers and commented out the print statements for the consumer threads' work, it only took around a minute. It is faster than 1 producer and 1 consumer.

But, there was a shocking thing for me to figure out.

```
./a.out ./FreeBSD9-orig.tar 1 10  50.27s user 348.18s system 498% cpu 1:19.94 total
```

**<Figure 12 - Execution time in 1 producer 10 consumer>**

```
./a.out ./FreeBSD9-orig.tar 1 100  126.24s user 2085.46s system 608% cpu 6:03.46 total
```

**<Figure 13 - Execution time in 1 producer 100 consumer>**

How come 1:100 is much slower than 1:10? Since it uses more threads to process, I thought it would finish quicker than 1:10. But it was not.

So, I asked chatGPT about why it was so.

The main reason was the lock contention, which means that consumer threads have to wait to access the single buffer. As the number of consumers increases, parallel processing becomes possible, which is why 1:10 is much faster than 1:1. However, if the number of threads becomes too large, the consumer threads end up waiting for a long time. Additionally, since I am using only one producer, it cannot provide sufficient data for multiple consumers, which could also be a reason.

# Goal 5) Implement N:M with K shared objects from 1:N

Let’s change a single producer to multiple producers to make it faster. I implemented multiple shared objects with a circular queue. In other words, I replaced the buffer with a circular queue.

Unlike 1:N, the shared object stores a single line from the input file at a time.

For example, with 3 producers and 5 consumers using 5 shared objects, each producer reads a single line from the input file and puts it in the shared object(so) in the following sequence.

The first producer: so[0] → so[1] → so[2] → so[3] → so[4]

The second producer: so[1] → so[2] → so[3] → so[4] → so[0]

The third producer: so[2] → so[3] → so[4] → so[0] → so[1]

Also, each consumer reads a single line from the shared object in the following sequence.

The first consumer: so[0] → so[1] → so[2] → so[3] → so[4]

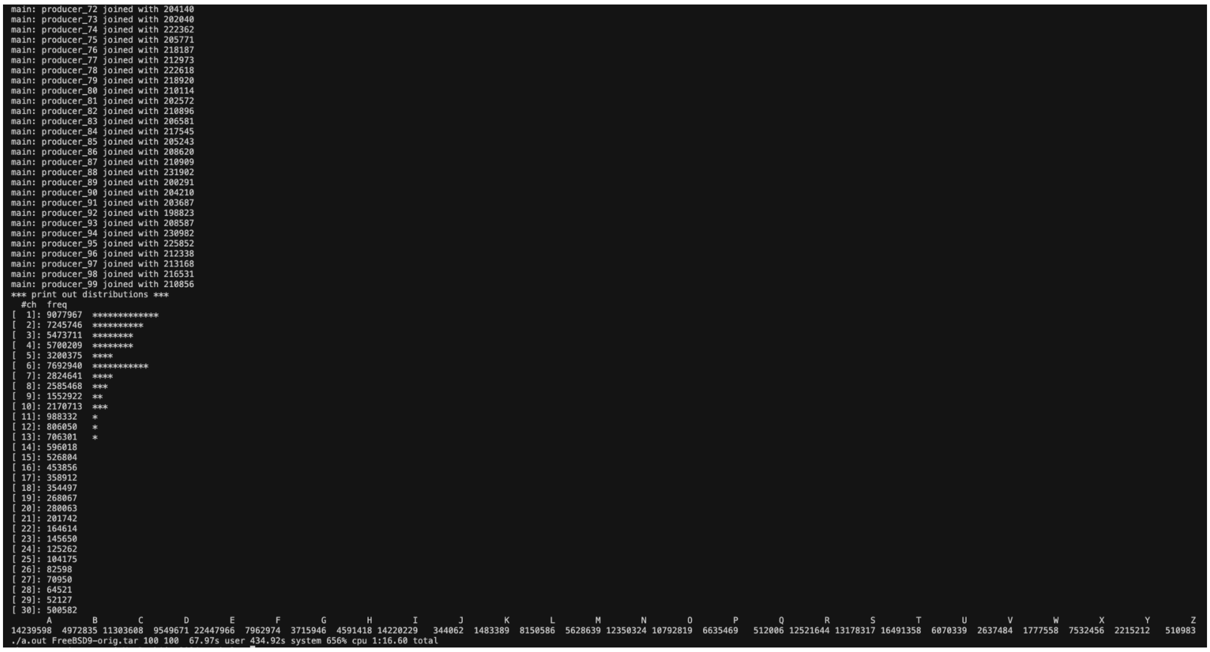
The second consumer: so[1] → so[2] → so[3] → so[4] → so[0]

The third consumer: so[2] → so[3] → so[4] → so[0] → so[1]

The fourth consumer: so[3] → so[4] → so[0] → so[1] → so[2]

The fifth consumer: so[4] → so[0] → so[1] → so[2] → so[3]

Also, as the number of producers reading the input file increases, I used a `file_lock` to avoid race condition. I also used a `global_done` variable to notify all threads(both producers and consumers) when the producer finish reading the input file. Additionally, I used a `global_done_lock` to ensure that only the producer who reads the last line of the input file can change the flag. Finally, I used a `so_index_lock` to make sure that each producer and consumer uses a different shared object in each thread.




**<Figure 14 - Success with FreeBSD9-orig.tar in 100 producer 100 consumer>**

As you can see, it took a minute and 16.60 seconds to execute, which is shorter than 1:1 or 1:N.

The performance did increase, but not as much as I expected. I thought that the performance would increase dramatically due to having multiple producers and multiple shared objects, but it wasn't. The reason was that the number of mutex locks increased. Acquiring and releasing mutex locks has high performance impact caused by frequent context switching penalty and overhead.

# Build

environment: **visual studio code**

programming language: **C**

compile: `gcc Nprod_Mcons.c`

execute: `./a.out FreeBSD9-orig.tar 100 100`

# Lesson

It was interesting to implement the concept of thread.

However, it was quite challenging because I've never used the pthread library before. While using functions from the library, ensuring proper synchronization between threads to avoid race conditions and deadlocks was one of the most difficult parts.

While implementing, it was surprising that the performance didn't dramatically improve from 1:1 to 1:N and from 1:N to N:M was surprising. Especially, the fact that acquiring and releasing mutex locks takes some time was one of the main reasons for only a slight, rather than dramatic, performance improvement from 1:N to N:M. According to Amdahl's Law, there is a fundamental limit to performance improvement, no matter how much the processors are parallelized.

When I began implementing N:M, I initially started with a single shared object. But I realized that this would be basically the same as 1:1. So, I tried implementing multiple shared objects using multiple buffers, with each producer mapped to a shared object, allowing each producer to read multiple lines from the input file independently. However, I discovered that this approach was still the same as 1:1. It's no difference from having multiple 1:1 pairs running independently. As a result, I changed multiple buffers to multiple circular queues. I realized that for N:M implementation to be effective, multiple shared objects are essential.

If time allows, I want to implement two types of N:M.

1) N:M with K shared objects using multiple buffers in a different algorithm from the one I used before.
2) N:M with K shared objects using a buffer and a circular queue.