Operating Systems Assignment

Due on 6 May, 2019

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Contents

Shared Resources and Mutual Exclusion

File IO

The log file is shared by all threads. Mutual exclusion is not needed for file IO since all POSIX functions which have a `FILE*` parameter call `flockfile`, or act as if they had and all my log functions use a single `fprintf` call each.

`http://pubs.opengroup.org/onlinepubs/9699919799/functions/flockfile.html`

Statistics

The statistics struct is shared by all cpu threads. Mutual exclusion is achieved by guarding access to the struct with a mutex.

Queue

All functions that can access data inside the queue struct hold a mutex whenever they are running.

Testing

The program will not work correctly if the numbers in the input file can not be parsed as `unsigned int`, this is due to using `fscanf` rather than a more robust function.

The program does not check for overflow when updating statistics.

Apart from these issues the program is working correctly.

Examples

I have not included `simulation_log` outputs in most of the examples below because they take up a lot of space, I have included gantt charts instead.

Example 1

Queue size: 7

Input

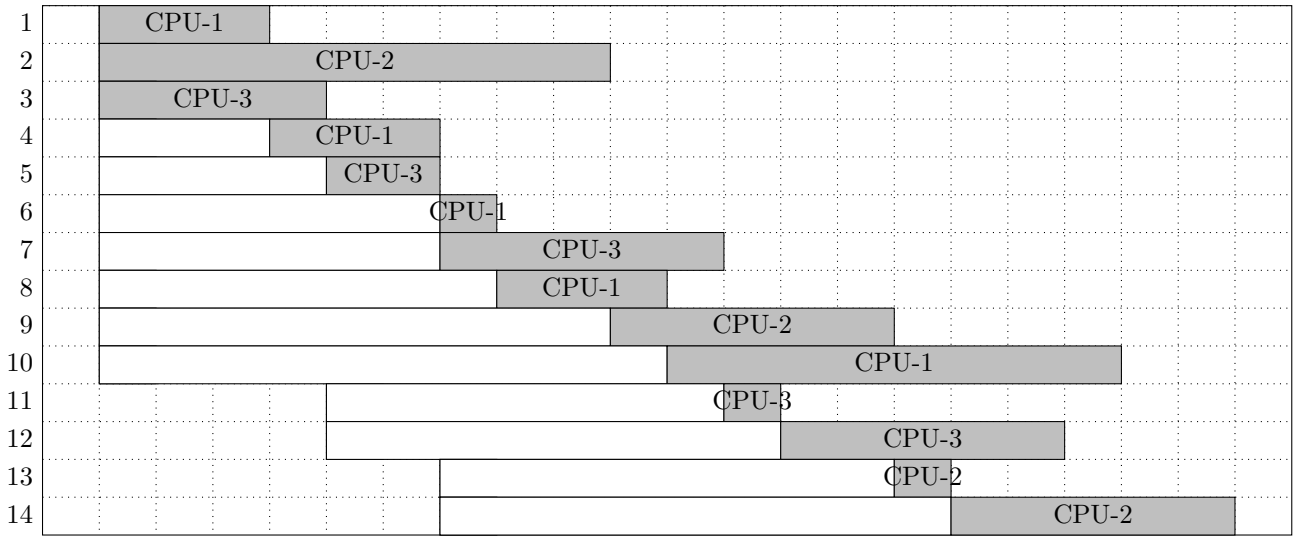
```
1 3
2 9
3 4
4 3
```

```
5 2
6 1
7 5
8 3
```

```
9 5
10 8
11 1
12 5
```

```
13 1
14 5
```

Chart



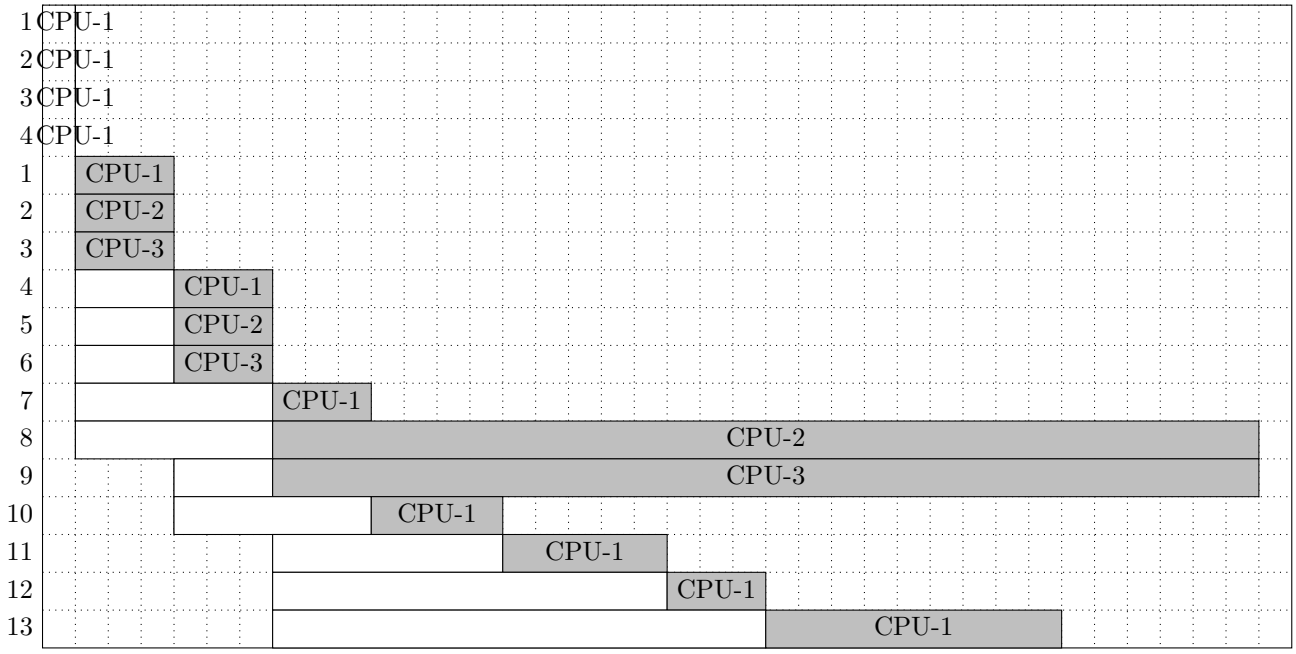
Example 2

Queue size: 5

Input

```
1 0
2 0
3 0
4 0
1 3
2 3
3 3
4 3
5 3
6 3
7 3
8 30
9 30
10 4
11 5
12 3
13 9
```

Chart



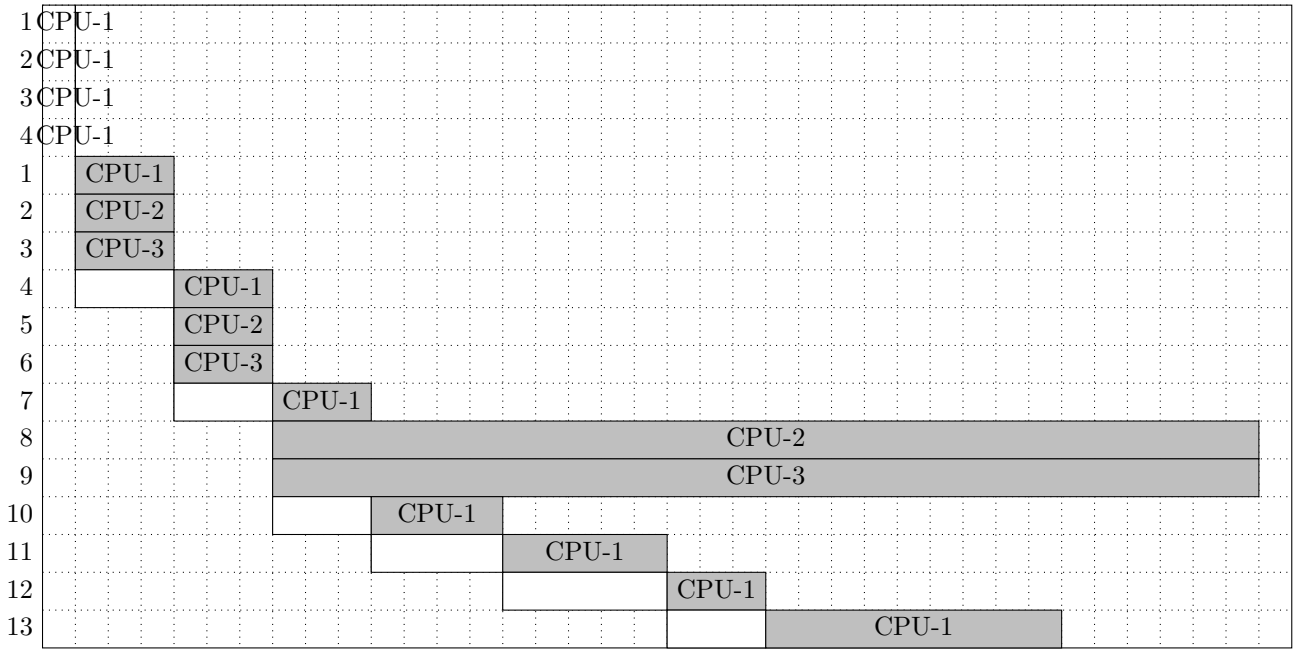
Example 3

Queue size: 1

Input

```
1 0
2 0
3 0
4 0
1 3
2 3
3 3
4 3
5 3
6 3
7 3
8 30
9 30
10 4
11 5
12 3
13 9
```

Chart



With Log

Queue size: 4

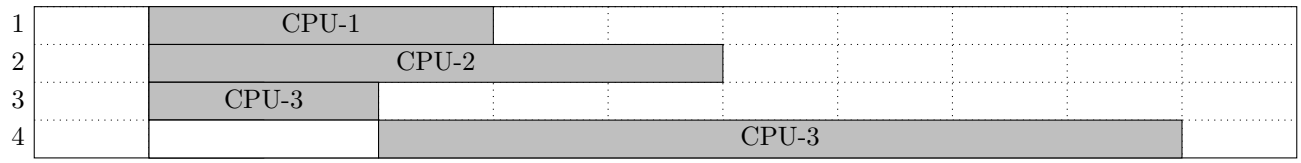
Input

```
1 3
2 5
3 2
4 7
```

Log

```
1: 3
Arrival time: 22:58:54

2: 5
Arrival time: 22:58:54

3: 2
Arrival time: 22:58:54

4: 7
Arrival time: 22:58:54

Number of tasks put into Ready-Queue: 4
Terminates at time: 22:58:54

Statistics for CPU 1:
Job #1
Arrival time: 22:58:54
Service time: 22:58:54

Statistics for CPU 2:
Job #2
Arrival time: 22:58:54
Service time: 22:58:54

Statistics for CPU 3:
Job #3
Arrival time: 22:58:54
Service time: 22:58:54

Statistics for CPU 3:
Job #3
Arrival time: 22:58:54
Completion time: 22:58:56

Statistics for CPU 3:
Job #4
Arrival time: 22:58:54
Service time: 22:58:56

Statistics for CPU 1:
Job #1
Arrival time: 22:58:54
Completion time: 22:58:57

CPU-1 terminates after servicing 1 tasks

Statistics for CPU 2:
Job #2
Arrival time: 22:58:54
Completion time: 22:58:59

CPU-2 terminates after servicing 1 tasks

Statistics for CPU 3:
Job #4
Arrival time: 22:58:54
Completion time: 22:59:03

CPU-3 terminates after servicing 2 tasks

Number of tasks: 4
Average waiting time: 0 seconds
Average turn around time: 4 seconds
```

Chart



Source Code

README.org

* Compiling

Compile =scheduler= by running =make= in this directory.

* Usage

=./scheduler [job file] [queue size]=

End of README.org

Makefile

```
.POSIX:
CC      = gcc
CFLAGS  = -std=c11 -Wall -g
LDFLAGS =
LDLIBS  = -lpthread

OBJS = build/cpu.o build/error.o build/log.o build/main.o build/task.o \
       build/tsqueue.o

scheduler: $(OBJS)
        $(CC) $(OBJS) $(LDFLAGS) $(LDLIBS) -o $@

build/cpu.o: src/cpu.c src/cpu.h src/tsqueue.h src/job.h src/log.h
        @mkdir -p build
        $(CC) $(CFLAGS) -c $< -o $@

build/error.o: src/error.c src/error.h
        @mkdir -p build
        $(CC) $(CFLAGS) -c $< -o $@

build/log.o: src/log.c src/log.h src/job.h src/config.h
        @mkdir -p build
        $(CC) $(CFLAGS) -c $< -o $@

build/main.o: src/main.c src/config.h src/cpu.h src/tsqueue.h src/task.h \
              src/error.h src/job.h
        @mkdir -p build
        $(CC) $(CFLAGS) -c $< -o $@

build/task.o: src/task.c src/task.h src/tsqueue.h src/job.h src/log.h
        @mkdir -p build
        $(CC) $(CFLAGS) -c $< -o $@

build/tsqueue.o: src/tsqueue.c src/tsqueue.h
        @mkdir -p build
        $(CC) $(CFLAGS) -c $< -o $@

clean:
        rm -rf build scheduler
```

End of Makefile

tsqueue.h

```
/**
 * @file   tsqueue.h
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Thread safe single-producer, multi-consumer FIFO queue.
 *
 * This is a thread safe single-producer, multi-consumer FIFO queue with the
 * following properties:
 * - Uses memory provided by the user for the queue itself, allowing the user
 *   to ensure any alignment requirements. This memory may already contain
 *   elements.
 * - Arbitrary queue element sizes.
 * - Supports pushing and popping multiple elements atomically.
 * - Leaves elements in the user provided memory after destroying the queue in
 *   the order they would have been popped.
 */

#ifndef TSQUEUE_H
#define TSQUEUE_H

#include <stdbool.h>
#include <stddef.h>
#include <limits.h>

/** Thread safe single-producer, multi-consumer FIFO queue. */
typedef struct tsqueue tsqueue;

/**
 * @brief Create a new tsqueue.
 *
 * @param[out] queue The tsqueue, will be NULL if creation fails.
 * @param[in] data Array used to store queue elements, must not be used until
 *                 tsqueue_destroy() is called.
 * @param capacity The number of elements that @p data can hold.
 * @param elem_size The size of an element in @p data.
 * @param used The number of items already in @p data, these elements will be
 *             accessible via tsqueue_pop(). The first element to be popped
 *             will be the first element of @p data.
 *
 * @return Zero if the function succeeds, else a POSIX error number.
 */
int tsqueue_create(tsqueue **queue, void *data, size_t capacity,
                   size_t elem_size, size_t used);

/**
 * @brief Forces all tsqueue_put() and tsqueue_pop() functions using this
 *        queue to exit and return TSQUEUE_CLOSED.
 *
 * Will block until all calls have exited. This function is intended to be
 * used before tsqueue_destroy as a way to signal to other threads that they
 * should stop reading from the queue. All future calls to tsqueue_put() and
 * tsqueue_pop() will also return TSQUEUE_CLOSED.
 *
 * @param[in] queue The tsqueue to close.
 */
```

```
void tsqueue_close(tsqueue *queue);

/**
 * @brief Calls tsqueue_close() before freeing resources allocated by tsqueue
 *        functions.
 *
 * Using a tsqueue while it is being destroyed or after it is destroyed will
 * cause undefined behaviour. tsqueue_close() and tsqueue_set_done() can be
 * useful for indicating to other threads that they should stop using the
 * queue.
 *
 * @param[in] queue The tsqueue to destroy.
 * @param[out] used The number of queue items left in the array provided to
 *                  tsqueue_create(). The first array element would have been
 *                  popped next. Can be NULL.
 */
void tsqueue_destroy(tsqueue *queue, size_t *used);

/**
 * @brief Returns the capacity of the queue.
 *
 * @param[in] queue The tsqueue.
 *
 * @return The capacity of @p queue.
 */
size_t tsqueue_capacity(tsqueue *queue);

/**
 * @brief Blocks until there are @p n_elems free spaces in the queue.
 *
 * @param[in] queue The tsqueue.
 * @param n_elems The number of elements to wait for.
 *
 * @return Zero if the function is successful.
 *
 *         TSQUEUE_CLOSED if the queue is closed.
 *
 *         TSQUEUE_TOO_MANY if @p n_elems is greater than the queue's
 *         capacity.
 *
 *         TSQUEUE_SINGLE_PRODUCER if a tsqueue_put() or
 *         tsqueue_wait_for_space() call is already running.
 */
int tsqueue_wait_for_space(tsqueue *queue, size_t n_elems);

/**
 * @brief Waits until there are @p n_elem free slots in the queue and then
 *        adds all elements to the end of the queue.
 *
 * The first element in @p in will be popped first, after all elements already
 * in the queue.
 *
 * @param[in] queue The tsqueue.
 * @param n_elems The number of elements in @p in.
 * @param[in] in The items to insert in to the queue.
 *
 * @return Zero if the function is successful.
 *
```

```
 *         TSQUEUE_CLOSED if the queue is closed.
 *
 *         TSQUEUE_TOO_MANY if @p n_elems is greater than the queue's
 *         capacity.
 *
 *         TSQUEUE_SINGLE_PRODUCER if a a tsqueue_put() or
 *         tsqueue_wait_for_space() call is already running.
 */
int tsqueue_put(tsqueue *queue, size_t n_elems, void *in);

/**
 * @brief Retrieve elements from a tsqueue.
 *
 * Will block until there is n_elems elements unless the queue is closed or
 * `tsqueue_set_done(queue, true)` has been called.
 *
 * @param[in] queue The tsqueue.
 * @param[in,out] n_elems The maximum number of elements to place in @p
 *                        out. Will be set to the actual number of elements
 *                        retrieved. Will be set to zero if the queue is
 *                        closed or `tsqueue_set_done(queue, true)` has been
 *                        called.
 * @param[out] out Buffer to place the elements in. The first element was
 *                 first in the queue.
 *
 * @return Zero if the function is successful, including when zero elements
 *         are retrieved.
 *
 *         TSQUEUE_CLOSED if the queue is closed.
 */
int tsqueue_pop(tsqueue *queue, size_t *n_elems, void *out);

/**
 * @brief Indicate that no more items will be placed in the queue. Can be
 *        reversed.
 *
 * @param[in] queue The tsqueue.
 * @param done True to indicate that no more items will be placed in the
 *             queue, false to reset to the normal state.
 */
void tsqueue_set_done(tsqueue *queue, bool done);

enum
{
    // The reason we use negative numbers is that POSIX errno
    // values are always positive. This allows us to return a POSIX error
    // value or a custom error value and differentiate between them.

    /** The queue was closed. */
    TSQUEUE_CLOSED = INT_MIN,

    /** tsqueue_put() was called with more items than the queue can hold. */
    TSQUEUE_TOO_MANY,

    /** A tsqueue_put() or tsqueue_wait_for_space() call was made while one
     * was already running. */
    TSQUEUE_SINGLE_PRODUCER
};
```

```
#endif /* TSQUEUE_H */
```

End of tsqueue.h

tsqueue.c

```c
/**
 * @file   tsqueue.c
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Implementation of tsqueue.
 */

#include "tsqueue.h"
#include <pthread.h>
#include <stdbool.h>
#include <stddef.h>
#include <string.h>
#include <stdlib.h>
#include <errno.h>

/** The internal structure of tsqueue. */
struct tsqueue
{
    /** The lock for the data in this struct. Must be held before reading or
     * writing any values in this struct. */
    pthread_mutex_t lock;

    /** The capacity of the queue. */
    size_t capacity;

    /** The number of used elements in the queue. */
    size_t used;

    /** The size of an element in the queue. */
    size_t elem_size;

    /** The actual data provided by the user. Currently this is just an array
     * where new elements are inserted at the end and everything is shifted
     * when elements are removed. */
    void *data;

    /** The number of unused elements that a producer is waiting for, or zero
     * if no producer is waiting. */
    size_t producer_n_elems;

    /** Used to signal the waiting producer to be called by consumers if they
     * find there is enough free elements after consuming some. */
    pthread_cond_t producer_wakeup;

    /** The number of waiting consumers. */
    size_t n_consumers_waiting;

    /** Used to signal waiting consumers. */
    pthread_cond_t consumer_wakeup;

    /** Used to signal to tsqueue_destroy() that all consumers and producers
     * have exited. */
    pthread_cond_t all_dead;

    /** Indicates that consumers should not wait for more items to be
```

```
     * inserted. */
    bool producers_done;

    /** Indicates that the queue is about to be destroyed and all functions
     * should return an error indicator. */
    bool die;
};

/**
 * @brief Wait for space in the queue, the queue lock must be held when
 *        calling this function.
 *
 * @param queue The queue.
 * @param n_elems Number of unused elements to wait for.
 *
 * @return Zero is successful, TSQUEUE_CLOSED if the queue is closed,
 *         else a POSIX error number.
 */
static int wait_for_space_internal(struct tsqueue *queue, size_t n_elems);

/**
 * @brief Signals queue.all_dead if there are no producers or consumers
 *        waiting, the queue lock must be held when calling this function.
 *
 * @param queue The queue.
 */
static void signal_if_all_dead(struct tsqueue *queue);

int tsqueue_create(struct tsqueue **queue, void *data, size_t capacity,
                   size_t elem_size, size_t used)
{
    int retval = 0;

    *queue = malloc(sizeof(**queue));

    if (queue == NULL) {
        retval = errno;
    }

    if (retval == 0) {
        **queue = (struct tsqueue){
            .capacity = capacity,
            .elem_size = elem_size,
            .data = data,
            .used = used
        };
    }

    int steps_done = 0;
    if (retval == 0)
    {
        retval = pthread_mutex_init(&(*queue)->lock, NULL);
    }

    if (retval == 0)
    {
        steps_done = 1;
        retval = pthread_cond_init(&(*queue)->producer_wakeup, NULL);
```

```
    }

    if (retval == 0)
    {
        steps_done = 2;
        retval = pthread_cond_init(&(*queue)->consumer_wakeup, NULL);
    }

    if (retval == 0)
    {
        steps_done = 3;
        retval = pthread_cond_init(&(*queue)->all_dead, NULL);
    }

    if (retval == 0)
    {
        steps_done = 4;
    }

    if  (retval != 0)
    {
        switch (steps_done)
        {
        case 4:
            pthread_cond_destroy(&(*queue)->all_dead);
            /* FALL THROUGH */
        case 3:
            pthread_cond_destroy(&(*queue)->consumer_wakeup);
            /* FALL THROUGH */
        case 2:
            pthread_cond_destroy(&(*queue)->producer_wakeup);
            /* FALL THROUGH */
        case 1:
            pthread_mutex_destroy(&(*queue)->lock);
            /* FALL THROUGH */
        default:
            break;
        }

        free(*queue);
    }

    return retval;
}

void tsqueue_close(struct tsqueue *queue)
{
    pthread_mutex_lock(&queue->lock);

    queue->die = true;

    if (queue->producer_n_elems != 0)
    {
        pthread_cond_signal(&queue->producer_wakeup);
    }

    for (size_t i = 0; i < queue->n_consumers_waiting; ++i)
    {
```

```
        pthread_cond_signal(&queue->consumer_wakeup);
    }

    while (queue->producer_n_elems != 0 && queue->n_consumers_waiting != 0)
    {
        pthread_cond_wait(&queue->all_dead, &queue->lock);
    }

    pthread_mutex_unlock(&queue->lock);
}

void tsqueue_destroy(struct tsqueue *queue, size_t *used)
{
    tsqueue_close(queue);

    if (used != NULL)
    {
        *used = queue->used;
    }

    pthread_mutex_destroy(&queue->lock);
    pthread_cond_destroy(&queue->producer_wakeup);
    pthread_cond_destroy(&queue->consumer_wakeup);
    pthread_cond_destroy(&queue->all_dead);
    free(queue);
}

size_t tsqueue_capacity(struct tsqueue *queue)
{
    pthread_mutex_lock(&queue->lock);
    size_t capacity = queue->capacity;
    pthread_mutex_unlock(&queue->lock);
    return capacity;
}

int tsqueue_wait_for_space(struct tsqueue *queue, size_t n_elems)
{
    pthread_mutex_lock(&queue->lock);
    int retval = wait_for_space_internal(queue, n_elems);
    pthread_mutex_unlock(&queue->lock);
    return retval;
}

int tsqueue_put(struct tsqueue *queue, size_t n_elems, void *in)
{
    int retval = 0;

    pthread_mutex_lock(&queue->lock);

    retval = wait_for_space_internal(queue, n_elems);

    if (retval == 0)
    {
        memcpy((char *)queue->data + (queue->used * queue->elem_size),
               in, n_elems * queue->elem_size);
        if (n_elems != 0 && queue->n_consumers_waiting != 0)
        {
            pthread_cond_signal(&queue->consumer_wakeup);
```

```
        }

        queue->used += n_elems;
    }

    pthread_mutex_unlock(&queue->lock);

    return retval;
}

int tsqueue_pop(struct tsqueue *queue, size_t *n_elems, void *out)
{
    int retval = 0;

    pthread_mutex_lock(&queue->lock);

    if (*n_elems > queue->capacity)
    {
        retval = TSQUEUE_TOO_MANY;
    }

    if (retval == 0)
    {
        ++queue->n_consumers_waiting;
        while (!queue->producers_done && !queue->die && queue->used < *n_elems)
        {
            pthread_cond_wait(&queue->consumer_wakeup, &queue->lock);
        }
        --queue->n_consumers_waiting;
    }

    if (queue->die)
    {
        retval = TSQUEUE_CLOSED;
        *n_elems = 0;
        signal_if_all_dead(queue);
    }

    if (retval == 0)
    {
        if (queue->used < *n_elems)
        {
            *n_elems = queue->used;
        }
        memcpy(out, queue->data, *n_elems * queue->elem_size);
        queue->used -= *n_elems;
        memmove(queue->data,
                (char *)queue->data + (*n_elems * queue->elem_size),
                queue->used * queue->elem_size);

        if (queue->producer_n_elems != 0
            && queue->producer_n_elems <= (queue->capacity - queue->used))
        {
            pthread_cond_signal(&queue->producer_wakeup);
        }

        if (queue->used != 0 && queue->n_consumers_waiting != 0)
        {
```

```
            pthread_cond_signal(&queue->consumer_wakeup);
        }
    }

    pthread_mutex_unlock(&queue->lock);

    return retval;
}

void tsqueue_set_done(struct tsqueue *queue, bool done)
{
    pthread_mutex_lock(&queue->lock);

    queue->producers_done = done;
    for (size_t i = 0; i < queue->n_consumers_waiting; ++i)
    {
        pthread_cond_signal(&queue->consumer_wakeup);
    }

    pthread_mutex_unlock(&queue->lock);
}

static int wait_for_space_internal(struct tsqueue *queue, size_t n_elems)
{
    int retval = 0;

    if (n_elems > queue->capacity)
    {
        retval = TSQUEUE_TOO_MANY;
    }

    if (queue->producer_n_elems != 0)
    {
        retval = TSQUEUE_SINGLE_PRODUCER;
    }

    if (retval == 0)
    {
        queue->producer_n_elems = n_elems;
        while (!queue->die && (queue->capacity - queue->used) < n_elems)
        {
            pthread_cond_wait(&queue->producer_wakeup, &queue->lock);
        }
        queue->producer_n_elems = 0;
    }

    if (queue->die)
    {
        retval = TSQUEUE_CLOSED;
        signal_if_all_dead(queue);
    }

    return retval;
}

static void signal_if_all_dead(struct tsqueue *queue)
{
    if (queue->producer_n_elems == 0 && queue->n_consumers_waiting == 0)
```

```
    {
        pthread_cond_signal(&queue->all_dead);
    }
}
```

End of tsqueue.c

task.h

```
/**
 * @file   task.h
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  The task() function described by the assignment spec.
 */

#ifndef TASK_H
#define TASK_H

#include "tsqueue.h"
#include <stdio.h>

/** Parameters to pass to task(). */
struct task_params
{
    /** The ready-queue, the task() thread only acts as a producer. */
    tsqueue *queue;

    /** The file to  get jobs from. */
    FILE *job_file;

    /** The buffer to store jobs in before placing them in the queue. */
    struct job_struct *job_buffer;

    /** The length of job_buffer. */
    size_t job_buffer_length;

    /** The file to write log messages to. */
    FILE *log_file;

    /** The return value of the task() call. task() will set this before
     * exiting. Zero if successful, otherwise can be passed to
     * errno_or_ae_to_str(). */
    int retval;
};

/**
 * @brief Places jobs in the provided queue until the end of the file is
 *        reached or an error occurs.
 *
 * @param data See task_params for details.
 *
 * @return NULL, see task_params for return value.
 */
void *task(void *data);

#endif /* TASK_H */
```

End of task.h

task.c

```c
/**
 * @file   task.c
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Implementation of task().
 */

#define _POSIX_C_SOURCE 200809L

#include "task.h"
#include "job.h"
#include "log.h"
#include "error.h"
#include <stdbool.h>
#include <stdint.h>
#include <stdio.h>
#include <errno.h>
#include <time.h>

/**
 * @brief Fill @p buffer with jobs from @p job_file.
 *
 * The file should contain "<job id> <job time in seconds> <job id> <job time
 * in seconds> ..." separated by whitespace.
 *
 * @param[in,out] job_file The file to read jobs from.
 * @param length The maximum number of jobs to read.
 * @param[out] buffer The buffer to fill with at most @p length jobs.
 * @param[out] used The number of jobs placed in the buffer. Zero if end of
 *                  file is reached.
 *
 * @return Zero if the function succeeds, else an error code that can be
 *         passed to errno_or_ae_to_str().
 */
static int fill_job_buffer(FILE *job_file, size_t length,
                           struct job_struct *buffer, size_t *used);

void *task(void *ptr)
{
    int retval = 0;

    // Input arguments
    struct task_params *params = ptr;
    tsqueue *queue = params->queue;
    FILE *job_file = params->job_file;
    struct job_struct *job_buffer = params->job_buffer;
    size_t job_buffer_length = params->job_buffer_length;
    FILE *log_file = params->log_file;

    // Total number of jobs processed
    unsigned long n_jobs = 0;

    if (tsqueue_capacity(queue) < job_buffer_length)
    {
        job_buffer_length = tsqueue_capacity(queue);
```

```
    }


    int queue_retval = 0;
    while (retval == 0 && !feof(job_file) && queue_retval == 0)
    {
        size_t jobs_in_buffer = 0;
        retval = fill_job_buffer(job_file, job_buffer_length, job_buffer,
                                 &jobs_in_buffer);
        if (retval == 0)
        {
            queue_retval = tsqueue_wait_for_space(queue, jobs_in_buffer);
        }

        if (retval == 0 && queue_retval == 0)
        {
            for (size_t i = 0; i < jobs_in_buffer; ++i)
            {
                clock_gettime(CLOCK_MONOTONIC, &job_buffer[i].arrival_mono);
                clock_gettime(CLOCK_REALTIME, &job_buffer[i].arrival_real);
            }
            queue_retval = tsqueue_put(queue, jobs_in_buffer, job_buffer);
            n_jobs += jobs_in_buffer;
        }

        if (retval == 0 && queue_retval == 0)
        {
            for (size_t i = 0; i < jobs_in_buffer; ++i)
            {
                retval = log_arrival(log_file, &job_buffer[i]);
                if (retval != 0)
                {
                    break;
                }
            }
        }
    }

    tsqueue_set_done(queue, true);

    if (retval == 0)
    {
        struct timespec time = {0};
        clock_gettime(CLOCK_REALTIME, &time);
        retval = log_task_done(log_file, time, n_jobs);
    }

    params->retval = retval;
    return NULL;
}

static int fill_job_buffer(FILE *job_file, size_t length,
                           struct job_struct *buffer, size_t *used)
{
    int retval = 0;

    *used = 0;
    while (!feof(job_file) && retval == 0 && *used < length)
```

```
    {
        // I have used fscanf rather than a more robust function here to keep
        // this function simple.
        struct job_struct *job = &buffer[*used];
        unsigned int tmp_time;
        errno = 0;
        if (fscanf(job_file, " %u %u ", &job->id, &tmp_time) != 2)
        {
            retval = (errno != 0) ? errno : AE_BAD_FILE;
        }
        else
        {
            job->cpu_burst = (time_t)tmp_time;
            ++*used;
        }
    }

    return retval;
}
```

End of task.c

cpu.h

```
/**
 * @file   cpu.h
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  The cpu() function described by the assignment spec.
 */

#ifndef CPU_H
#define CPU_H

#include "tsqueue.h"
#include <stdio.h>
#include <time.h>
#include <pthread.h>

/** Parameters to pass to cpu(). */
struct cpu_params
{
    /** Statistics shared between all cpu() threads. */
    struct cpu_shared_stats *stats;

    /** The ready-queue, cpu() threads only act as consumers. */
    tsqueue *queue;

    /** The id of the cpu to be used for logging. */
    unsigned id;

    /** The file to write log messages to. */
    FILE *log_file;

    /** The return value of the cpu() call. cpu() will set this before
     * exiting. Zero is successful, otherwise can be passed to
     * errno_or_ae_to_str(). */
    int retval;
};

/** Statistics shared between all cpu() calls. */
struct cpu_shared_stats
{
    /** Lock for the data in this struct. All cpu() threads must hold this
     * lock when reading or writing any of the values in this struct. */
    pthread_mutex_t lock;

    /** Total amount of time spent waiting by jobs in the ready queue. */
    time_t total_waiting_time;

    /** Total amount of time spent by jobs waiting in the queue or
     * running. */
    time_t total_turnaround_time;

    /** Number of jobs which have been inserted in to the queue. */
    unsigned long num_tasks;
};

/**
```

```
 * @brief Runs jobs from the provided queue until the queue is empty or an
 *        error occurs.
 *
 * @param data See cpu_params for details.
 *
 * @return NULL, see cpu_params for return value.
 */
void *cpu(void *data);

#endif /* CPU_H */
```

End of cpu.h

cpu.c

```c
/**
 * @file   cpu.c
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Implementation of cpu().
 */

#define _POSIX_C_SOURCE 200809L

#include "cpu.h"
#include "job.h"
#include "log.h"
#include <pthread.h>
#include <time.h>
#include <errno.h>
#include <stdio.h>

/**
 * @brief Logs service time, waits for @p job.cpu_burst seconds, then logs
 *        completion time. Also increments all values in @p stats.
 *
 * Calls log_service() before waiting and log_completion() after.
 *
 * @param[in] job The job to handle.
 * @param[in,out] log_file The file to log to.
 * @param cpu_id The id to be used in log messages.
 * @param[in,out] stats Stats to modify.
 *
 * @return Zero if the function succeeds, else an error code that can be
 *         passed to errno_or_ae_to_str().
 */
static int handle_job(struct job_struct *job, FILE *log_file, unsigned cpu_id,
                      struct cpu_shared_stats *stats);

void *cpu(void *ptr)
{
    int retval = 0;

    // Input arguments
    struct cpu_params *params = ptr;
    struct cpu_shared_stats *stats = params->stats;
    tsqueue *queue = params->queue;
    unsigned cpu_id = params->id;
    FILE *log_file = params->log_file;

    // Total number of jobs inserted
    unsigned long n_jobs = 0;

    size_t jobs_from_queue = 1;
    // The only time this will be non-zero is if the queue is closed due to an
    // error occurring elsewhere.
    int queue_retval;
    do
    {
        struct job_struct job;
```

```
        queue_retval = tsqueue_pop(queue, &jobs_from_queue, &job);
        if (jobs_from_queue == 1 && queue_retval == 0)
        {
            ++n_jobs;
            retval = handle_job(&job, log_file, cpu_id, stats);
        }
    } while (retval == 0 && jobs_from_queue == 1 && queue_retval == 0);

    if (retval == 0 && queue_retval == 0)
    {
        retval = log_cpu_done(log_file, cpu_id, n_jobs);
    }

    params->retval = retval;
    return NULL;
}



static void run_job(const struct job_struct *job)
{
    struct timespec ts = {.tv_sec = job->cpu_burst};
    // I have chosen to use clock_nanosleep instead of sleep here because it
    // allows us to use a monotonic clock explicitly.
    while (clock_nanosleep(CLOCK_MONOTONIC, 0, &ts, &ts) != 0)
    {
    }
}

static int handle_job(struct job_struct *job, FILE *log_file, unsigned cpu_id,
                      struct cpu_shared_stats *stats)
{
    int retval = 0;

    clock_gettime(CLOCK_MONOTONIC, &job->service_mono);
    clock_gettime(CLOCK_REALTIME, &job->service_real);

    pthread_mutex_lock(&stats->lock);
    ++stats->num_tasks;
    stats->total_waiting_time +=
        job->service_mono.tv_sec - job->arrival_mono.tv_sec;
    pthread_mutex_unlock(&stats->lock);

    retval = log_service(log_file, cpu_id, job);
    if (retval == 0)
    {
        run_job(job);
        clock_gettime(CLOCK_MONOTONIC, &job->completion_mono);
        clock_gettime(CLOCK_REALTIME, &job->completion_real);

        pthread_mutex_lock(&stats->lock);
        stats->total_turnaround_time +=
            job->completion_mono.tv_sec - job->arrival_mono.tv_sec;
        pthread_mutex_unlock(&stats->lock);

        retval = log_completion(log_file, cpu_id, job);
    }
```

```
    return retval;
}
```

End of cpu.c

main.c

```
/**
 * @file   main.c
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  User interaction and initialisation for other functions.
 */


#include "config.h"
#include "cpu.h"
#include "task.h"
#include "error.h"
#include "tsqueue.h"
#include "job.h"
#include "log.h"
#include <errno.h>
#include <stdint.h>
#include <pthread.h>
#include <stdio.h>
#include <stdlib.h>
#include <stdbool.h>
#include <inttypes.h>

/**
 * @brief Returns errno if @p ptr is NULL, else returns 0. Used to make main()
 *        a little bit cleaner.
 *
 * @param ptr The pointer to check.
 *
 * @return errno if @p ptr is NULL, else zero.
 */
static int errno_if_null(void *ptr);

int main(int argc, char **argv)
{
    // This function is very long but most of it is just braces and
    // whitespace.

    int retval = 0;

    FILE *log_file = NULL;
    FILE *input_file = NULL;
    pthread_t *cpu_threads = NULL;
    pthread_t task_thread;
    struct cpu_params *cpu_params = NULL;
    struct cpu_shared_stats stats = {0};
    struct task_params task_params = {0};
    struct job_struct *queue_data = NULL;
    tsqueue *queue = NULL;
    bool shared_is_initialised = false;
    size_t queue_length = 0;

    if (argc != 3)
    {
        retval = AE_WRONG_NUM_ARGS;
```

```
}

/*****************************************************/
/* BEGINNING OF PARSING AND RESOURCE ALLOCATION CODE */
/*****************************************************/

if (retval == 0)
{
    char *end;
    errno = 0;
    uintmax_t tmp = strtoumax(argv[2], &end, 10);
    if (errno)
    {
        retval = errno;
    }
    else if (tmp < QUEUE_SIZE_MIN || tmp > QUEUE_SIZE_MAX)
    {
        retval = EINVAL;
    }
    else
    {
        queue_length = (size_t)tmp;
    }
}

if (retval == 0)
{
    retval = pthread_mutex_init(&stats.lock, NULL);
    if (retval == 0)
    {
        shared_is_initialised = true;
    }
}

if (retval == 0)
{
    retval = errno_if_null(log_file = fopen(LOG_FILE_PATH, "a"));
}

if (retval == 0)
{
    retval = errno_if_null(input_file = fopen(argv[1], "r"));
}

if (retval == 0)
{
    retval =
        errno_if_null(cpu_threads = malloc(sizeof(*cpu_threads) * CPU_COUNT));
}

if (retval == 0)
{
    retval =
        errno_if_null(cpu_params = malloc(sizeof(*cpu_params) * CPU_COUNT));
}

if (retval == 0)
{
```

```
        retval =
            errno_if_null(queue_data = malloc(sizeof(*queue_data) * queue_length));
    }

    if (retval == 0)
    {
        retval = tsqueue_create(&queue, queue_data, queue_length,
                                sizeof(*queue_data), 0);
    }

    if (retval == 0)
    {
        for (unsigned int i = 0; i < CPU_COUNT; ++i)
        {
            cpu_params[i] = (struct cpu_params){
                .stats = &stats,
                .queue = queue,
                .id = i + 1,
                .log_file = log_file
            };
        }

        task_params = (struct task_params){
            .queue = queue,
            .job_file = input_file,
            .job_buffer_length = TASK_JOB_BUFFER_LENGTH,
            .log_file = log_file
        };
        retval = errno_if_null(task_params.job_buffer =
                                   malloc(sizeof(*task_params.job_buffer)
                                          * task_params.job_buffer_length));
    }

    /*****************************************/
    /* END OF PARSING AND RESOURCE ALLOCATION */
    /*****************************************/

    if (retval == 0)
    {
        retval = pthread_create(&task_thread, NULL, &task, &task_params);
    }

    if (retval == 0)
    {
        size_t i = 0;
        while (retval == 0 && i < CPU_COUNT)
        {
            retval =
                pthread_create(&cpu_threads[i], NULL, &cpu, &cpu_params[i]);
            ++i;
        }

        if (retval != 0)
        {
            tsqueue_close(queue);
            --i;
        }
```

```
        pthread_join(task_thread, NULL);
        for (size_t j = 0; j < i; ++j)
        {
            pthread_join(cpu_threads[j], NULL);
            if (retval == 0)
            {
                retval = cpu_params[j].retval;
            }
        }

        if (retval == 0)
        {
            retval = task_params.retval;
        }

    }

    if (retval == 0)
    {
        retval = log_main_done(log_file, &stats);
    }

    /*****************************/
    /* BEGINNING OF TEARDOWN CODE */
    /*****************************/

    if (retval != 0)
    {
        fprintf(stderr, "%s\nUsage: %s [job file] [queue size]\n",
                errno_or_ae_to_str(retval), argv[0]);
    }

    if (queue != NULL)
    {
        tsqueue_destroy(queue, NULL);
    }

    if (input_file != NULL)
    {
        fclose(input_file);
    }

    if (log_file != NULL)
    {
        fclose(log_file);
    }

    if (shared_is_initialised)
    {
        pthread_mutex_destroy(&stats.lock);
    }

    free(task_params.job_buffer);
    free(cpu_params);
    free(cpu_threads);
    free(queue_data);

    /***********************/
```

```
    /* END OF TEARDOWN CODE */
    /************************/

    return retval;
}

static int errno_if_null(void *ptr)
{
    return (ptr == NULL) ? errno : 0;
}
```

End of main.c

log.h

```
/**
 * @file   log.h
 * @author Liam Powell
 * @date   2019-04-28
 *
 * @brief  Logging functions used throughout the program.
 */


#ifndef LOG_H
#define LOG_H

#include "job.h"
#include "cpu.h"
#include <stdio.h>
#include <time.h>

/**
 * @brief Log the service of @p j at @p time to the file @p log_file.
 *
 * Uses the format:
 *
 *     Statistics for CPU-<cpu_id>:
 *     Job #<j.id>
 *     Arrival time: <j.arrival>
 *     Service time: <j.end>
 *
 * @param[in,out] log_file The file to write to.
 * @param cpu_id The id of the cpu.
 * @param[in] job The job to be logged.
 *
 * @return Zero if the function succeeds, else a POSIX error number.
 */
int log_service(FILE *log_file, unsigned cpu_id, const struct job_struct *job);

/**
 * @brief Log the completion of @p j at @p time to the file @p log_file.
 *
 * Uses the format:
 *
 *     Statistics for CPU-<cpu_id>:
 *     Job #<j.id>
 *     Arrival time: <j.arrival>
 *     Completion time: <j.end>
 *
 * @param[in,out] log_file The file to write to.
 * @param cpu_id The id of the cpu.
 * @param[in] job The job to be logged.
 *
 * @return Zero if the function succeeds, else a POSIX error number.
 */
int log_completion(FILE *log_file, unsigned cpu_id, const struct job_struct *job);

/**
 * @brief Log the total number of jobs executed by a cpu thread.
 *
```

```
 * Uses the format:
 *
 *     CPU-<cpu_id> terminates after servicing <n_jobs> tasks
 *
 * @param[in,out] log_file The file to write to.
 * @param cpu_id The id of the cpu.
 * @param n_jobs The number of jobs.
 *
 * @return Zero if the function succeeds, else a POSIX error number.
 */
int log_cpu_done(FILE *log_file, unsigned cpu_id, unsigned long n_jobs);

/**
 * @brief Log the arrival of a job.
 *
 * Uses the format:
 *
 *     <j.id>: <j.cpu_burst>
 *     Arrival time: <j.arrival>
 *
 * @param[in,out] log_file The file to write to.
 * @param[in] job The job to log.
 *
 * @return Zero if the function succeeds, else a POSIX error number.
 */
int log_arrival(FILE *log_file, const struct job_struct *job);

/**
 * @brief Log the total number of jobs put in to the queue by task().
 *
 * @param[in,out] log_file The file to write to.
 * @param time The time to add to the log.
 * @param n_jobs The number of jobs to add to the log.
 *
 * Uses the format:
 *
 *     Number of tasks put into Ready-Queue: <n_jobs>
 *     Terminates at time: <time>
 *
 * @return Zero if the function succeeds, else an error code that can be
 *         passed to errno_or_ae_to_str().
 */
int log_task_done(FILE *log_file, struct timespec time, unsigned long n_jobs);

/**
 * @brief Log statistics after all tasks are finished.
 *
 * Uses the format:
 * @verbatim
 * Number of tasks: #
 * Average waiting time: # seconds
 * Average turn around time: # seconds
 * @endverbatim
 *
 * @param log_file The file to write to.
 * @param stats The stats to get data from.
 *
 * @return Zero if the function succeeds, else an error code that can be
```

```
 *          passed to errno_or_ae_to_str().
 */
int log_main_done(FILE *log_file, struct cpu_shared_stats *stats);

#endif /* LOG_H */
```

End of log.h

log.c

```c
/**
 * @file   log.c
 * @author Liam Powell
 * @date   2019-04-28
 *
 * @brief  Implementation of log.h.
 */


#define _POSIX_C_SOURCE 200809L

#include "log.h"
#include "job.h"
#include "config.h"
#include "cpu.h"
#include <stdio.h>
#include <time.h>
#include <errno.h>
#include <stdint.h>

/**
 * @brief Log the job @p j and the event @p event at @p time to @p log_file.
 *
 * Uses the format:
 *
 *     Statistics for CPU-<cpu_id>:
 *     Job #<j.id>
 *     Arrival time: <j.arrival>
 *     <time> time: <j.end>
 *
 * @param[in,out] log_file The file to write to.
 * @param cpu_id The id of the cpu.
 * @param[in] job The job to be logged.
 * @param time The time for the event.
 * @param[in] event The event to log.
 *
 * @return Zero if the function succeeds, else an error code that can be
 *         passed to errno_or_app_errnum_to_str().
 */
static int log_cpu_event(FILE *log_file, unsigned cpu_id,
                         const struct job_struct *job, struct timespec time,
                         const char *event)
{
    int retval = 0;

    struct tm arrival_tm;
    struct tm event_tm;
    if (localtime_r(&job->arrival_real.tv_sec, &arrival_tm) == NULL
        || localtime_r(&time.tv_sec, &event_tm) == NULL)
    {
        retval = errno;
    }
    else
    {
        int res = fprintf(log_file,
                          "Statistics for CPU %u:\n"
```

```
                            "Job #%u\n"
                            "Arrival time: %02d:%02d:%02d\n"
                            "%s time: %02d:%02d:%02d\n\n",
                            cpu_id, job->id, arrival_tm.tm_hour,
                            arrival_tm.tm_min, arrival_tm.tm_sec, event,
                            event_tm.tm_hour, event_tm.tm_min, event_tm.tm_sec);
        if (res < 0)
        {
            retval = errno;
        }
    }

    return retval;
}

int log_service(FILE *log_file, unsigned cpu_id, const struct job_struct *job)
{
    return log_cpu_event(log_file, cpu_id, job, job->service_real, "Service");
}

int log_completion(FILE *log_file, unsigned cpu_id, const struct job_struct *job)
{
    // This is used to make the gantt charts in my report.
#ifdef CONFIG_STDOUT_PGFGANTT
    printf("%jd.%09lu "
           "\\ganttset{bar/.append style={fill=white}} "
           "\\ganttbar{%u}{%jd}{%jd} "
           "\\ganttbar[inline]{}{%jd}{%jd} "
           "\\ganttset{bar/.append style={fill=lightgray}} "
           "\\ganttbar[inline]{CPU-%u}{%jd}{%jd}\\\\\n",
           (intmax_t)job->arrival_mono.tv_sec,
           job->arrival_mono.tv_nsec, job->id,
           (intmax_t)job->arrival_mono.tv_sec,
           (intmax_t)job->arrival_mono.tv_sec - 1,
           (intmax_t)job->arrival_mono.tv_sec,
           (intmax_t)job->service_mono.tv_sec - 1, cpu_id,
           (intmax_t)job->service_mono.tv_sec,
           (intmax_t)job->completion_mono.tv_sec - 1);
#endif
    return log_cpu_event(log_file, cpu_id, job, job->completion_real,
                         "Completion");
}

int log_cpu_done(FILE *log_file, unsigned cpu_id, unsigned long n_jobs)
{
    int retval = 0;

    int res = fprintf(log_file,
                      "CPU-%u terminates after servicing %lu tasks\n\n",
                      cpu_id, n_jobs);
    if (res < 0)
    {
        retval = res;
    }

    return retval;
}
```

```
int log_task_done(FILE *log_file, struct timespec time, unsigned long n_jobs)
{
    int retval = 0;

    struct tm tm;
    if (localtime_r(&time.tv_sec, &tm) == NULL)
    {
        retval = errno;
    }
    else
    {
        int res = fprintf(log_file,
                          "Number of tasks put into Ready-Queue: %lu\n"
                          "Terminates at time: %02d:%02d:%02d\n\n",
                          n_jobs, tm.tm_hour, tm.tm_min,
                          tm.tm_sec);
        if (res < 0)
        {
            retval = res;
        }
    }

    return retval;
}

int log_arrival(FILE *log_file, const struct job_struct *job)
{
    int retval = 0;

    struct tm tm;
    if (localtime_r(&job->arrival_real.tv_sec, &tm) == NULL)
    {
        retval = errno;
    }
    else
    {
        int res = fprintf(log_file,
                          "%u: %jd\n"
                          "Arrival time: %02d:%02d:%02d\n\n",
                          job->id, (intmax_t)job->cpu_burst, tm.tm_hour,
                          tm.tm_min, tm.tm_sec);
        if (res < 0)
        {
            retval = errno;
        }
    }

    return retval;
}

int log_main_done(FILE *log_file, struct cpu_shared_stats *stats)
{
    uintmax_t avg_wait = 0;
    uintmax_t avg_turn = 0;
    if (stats->num_tasks != 0)
    {
        avg_wait = (uintmax_t)stats->total_waiting_time / stats->num_tasks;
        avg_turn = (uintmax_t)stats->total_turnaround_time / stats->num_tasks;
```

```
    }
    int retval =
        fprintf(log_file,
                "Number of tasks: %lu\n"
                "Average waiting time: %ju seconds\n"
                "Average turn around time: %ju seconds\n\n",
                stats->num_tasks, avg_wait, avg_turn);
    return (retval < 0) ? errno : 0;
}
```

End of log.c

config.h

```
/**
 * @file   config.h
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Constants used to configure the rest of the program.
 */

#ifndef CONFIG_H
#define CONFIG_H

#include <stddef.h>

/** The number of cpu function threads to spawn. */
static const unsigned int CPU_COUNT = 3;

/** The minimum size of the job queue. */
static const size_t QUEUE_SIZE_MIN = 1;

/** The maximum size of the job queue. */
static const size_t QUEUE_SIZE_MAX = 10;

/** The number of jobs for the task function to buffer before inserting in to
 * the queue. */
static const size_t TASK_JOB_BUFFER_LENGTH = 2;

/** The path of the simulation log to write to. */
static const char *const LOG_FILE_PATH = "simulation_log";

#endif /* CONFIG_H */
```

End of config.h

job.h

```
/**
 * @file   job.h
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Data structure for representing jobs.
 */

#ifndef JOB_H
#define JOB_H

#include <time.h>

/** Information about a job. All values are set by task(). */
struct job_struct {
    /** ID of the job. */
    unsigned id;

    /** Time required for the job in seconds. */
    time_t cpu_burst;

    /** Arrival time of the job from CLOCK_MONOTONIC. Used for statistics,
     * CLOCK_REALTIME is not appropriate for this as it can change
     * dramatically for various reasons (such as switching to daylight savings
     * time). */
    struct timespec arrival_mono;

    /** Arrival time of the job from CLOCK_REALTIME. Used in logs. */
    struct timespec arrival_real;

    /** Service time of the job from CLOCK_MONOTONIC. Used for statistics. */
    struct timespec service_mono;

    /** Service time of the job from CLOCK_REALTIME. Used for logs. */
    struct timespec service_real;

    /** Completion time of the job from CLOCK_MONOTONIC. Used for statistics. */
    struct timespec completion_mono;

    /** Completion time of the job from CLOCK_REALTIME. Used for logs. */
    struct timespec completion_real;
};

#endif /* JOB_H */
```

End of job.h

error.h

```
/**
 * @file   error.h
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Error reporting functions.
 */

#ifndef ERROR_H
#define ERROR_H

#include <limits.h>

// AE stands for application errno

enum ae_codes {
    // The reason we use negative numbers is that POSIX errno values are
    // always positive. This allows us to return a POSIX error value or a
    // custom error value and differentiate between them.

    /** Argument did not represent a number. */
    AE_STR_NOT_A_NUMBER = INT_MIN,

    /** The program was called with the wrong number of arguments. */
    AE_WRONG_NUM_ARGS,

    /** The file could not be parsed. */
    AE_BAD_FILE
};

/**
 * @brief Converts an application error value or an errno value to a
 *        string. Not thread safe.
 *
 * @param err The error number to convert.
 *
 * @return String relevant to the error.
 */
char *errno_or_ae_to_str(int err);

#endif /* ERROR_H */
```

End of error.h

error.c

```c
/**
 * @file   error.c
 * @author Liam Powell
 * @date   2019-04-25
 *
 * @brief  Implementation of error reporting functions.
 */

#include "error.h"
#include <string.h>

char *errno_or_ae_to_str(int err)
{
    char *retval = "Unknown error.";

    if (err >= 0)
    {
        retval = strerror(err);
    }
    else
    {
        switch ((enum ae_codes)err)
        {
        case AE_STR_NOT_A_NUMBER:
            retval = "Argument was not a number.";
            break;
        case AE_WRONG_NUM_ARGS:
            retval = "Wrong number of arguments.";
            break;
        case AE_BAD_FILE:
            retval = "File could not be parsed.";
        }
    }

    return retval;
}
```

End of error.c