Multi-threading using Thread Pool Pattern

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Outline

1. The Problem
2. The Solution Design
3. The Example Code
4. Conclusion

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The Problem

factorize – a multi-threaded program

- Factorizes natural numbers concurrently
- Reads numbers from standard input
- Writes result to the standard output
- Use thread pool pattern: main and workers
- Number of workers as command line argument $-t$
- Input numbers space: unsigned 64-bit integers

Development tools

- The **C** language
- POSIX pthread library

Sample invocation - I

```
$ cat <<_end_ | ./factorize -t 5
> a 12
> b 234
> _end_
a 12 = 2 2 3
b 234 = 2 3 3 13
```

Number **tag**

- Every number is prefixed with a tag
- Result to request matching
- Tag content is arbitrary
- No white space and control characters

Sample invocation - II

```
$ cat <<_end_ | ./factorize -t 5
> a 18446744
> b 18446744
> c 18446744
> _end_
c 18446744 = 2 2 2 349 6607
a 18446744 = 2 2 2 349 6607
b 18446744 = 2 2 2 349 6607
```

Observation

- The same number is factorized multiple times concurrently
- The results appear in different order on the standard output

Detailed requirements

Main thread

- Reads numbers from standard input
- Places the numbers into a queue
- Receives results from each worker
- Writes result to the standard output

Worker thread

- Picks up a number from the queue
- Computes factors for the picked number
- Passes the result back to the main thread

Program exit condition

- End of standard input **and** no busy threads anymore

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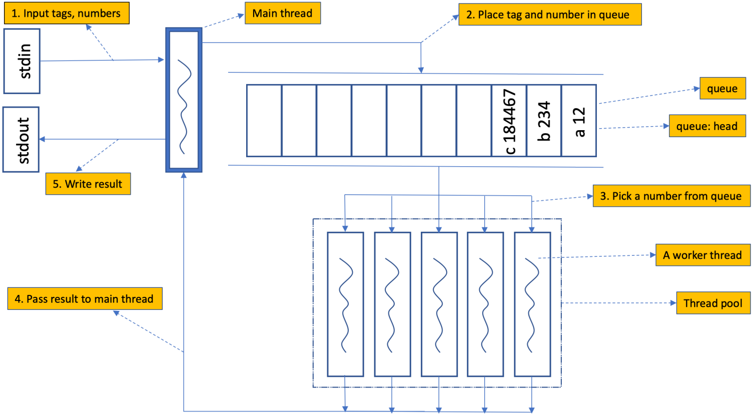
Architectural Design



Design considerations

The Queue

- The queue is accessed by multiple threads – Mutual exclusion: mutex
- What if the queue is empty – Condition variable: full
- What if the queue is full – Condition variable: empty
- How to detect the end of standard input?

The factorize function

- The seive of Eratosthenes method

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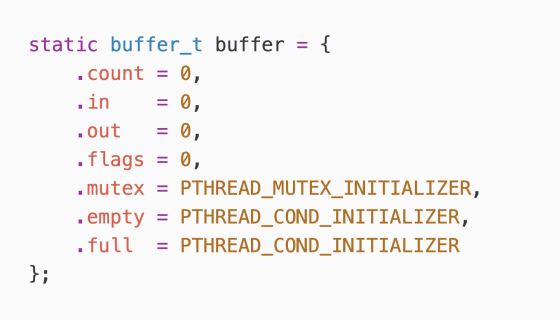
The data structures (buffer_t alias queue)

```
typedef struct {
    unsigned int    count;
    char            tag[BUFFER_SIZE][TAG_SIZE];
    unsigned long   data[BUFFER_SIZE];
    int             in;
    int             out;
    int             flags;
    pthread_mutex_t mutex;
    pthread_cond_t  empty;
    pthread_cond_t  full;
} buffer_t;
```

The data structures (queue initialization)



```c
static buffer_t buffer = {
    .count = 0,
    .in    = 0,
    .out   = 0,
    .flags = 0,
    .mutex = PTHREAD_MUTEX_INITIALIZER,
    .empty = PTHREAD_COND_INITIALIZER,
    .full  = PTHREAD_COND_INITIALIZER
};
```

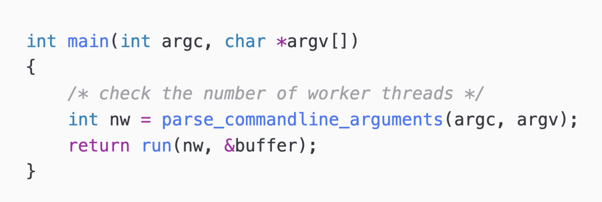
The data structures (completed task, thread_yield)

```
typedef struct {
    char* tag;
    unsigned long int nat_num;
    unsigned long int* factors;
    int count;
} completed_task_t;

typedef struct {
    completed_task_t** completed_tasks_list;
    int count; /* completed tasks by a thread */
} thread_yield_t;
```

The function prototypes

```c
/* function prototypes */
int main(int, char **);

static int parse_commandline_arguments(int, char**);
static int run(int, buffer_t*);

static int create_thread_pool(int, pthread_t**, buffer_t*);
static void read_numbers_from_stdin(buffer_t*);
static int thread_join(int, pthread_t*, thread_yield_t**);
static void write_to_standard_output(int, thread_yield_t**);
static void free_heap_memory(int, pthread_t*, thread_yield_t**);

static void enqueue(buffer_t*, char*, unsigned long);
static int dequeue(buffer_t*, char**, unsigned long**);

static void* worker(void*);
static completed_task_t* compute_factors(unsigned long);
```

The main(...) function



```
int main(int argc, char *argv[])
{
    /* check the number of worker threads */
    int nw = parse_commandline_arguments(argc, argv);
    return run(nw, &buffer);
}
```

The parse_commandline_arguments(...) function

```c
/* parse command line arguments */
static int parse_commandline_arguments(int argc, char *argv[])
{
    int c;
    int nw = 3;
    while ((c = getopt(argc, argv, "t:h")) >= 0) {
        switch (c) {
            case 't':
                if ((nw = atoi(optarg)) <= 0) {
                    fprintf(stderr, "Number of worker threads must be > 0\n");
                    exit(EXIT_FAILURE);
                }
                break;
            case 'h':
                printf("Usage: %s [-t num-worker] [-h]\n", progname);
                exit(EXIT_SUCCESS);
        }
    }
    return nw;
}
```

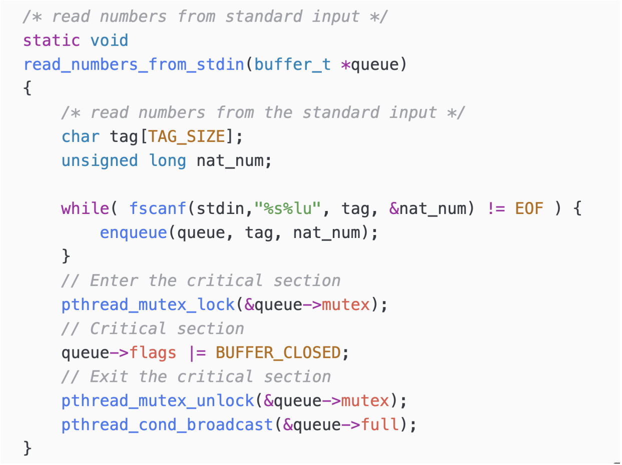
The run(...) function

```c
static int
run(int nw, buffer_t *queue)
{
    pthread_t* thread;
    thread_yield_t* yield_of_thread[nw];
    //
    if(create_thread_pool(nw, &thread, queue) == EXIT_FAILURE) return EXIT_FAILURE;
    // take input from stdin
    read_numbers_from_stdin(queue); // take input from stdin and populate the queue
    // thread join
    if(thread_join(nw, thread, (thread_yield_t**)&yield_of_thread) == EXIT_FAILURE)
        return EXIT_FAILURE;;
    // display output
    write_to_standard_output(nw, (thread_yield_t**)&yield_of_thread);
    // release dynamically acquired memory
    free_heap_memory(nw, thread, (thread_yield_t**)&yield_of_thread);
    //
    return EXIT_SUCCESS;
}
```

The create_thread_pool(...) function

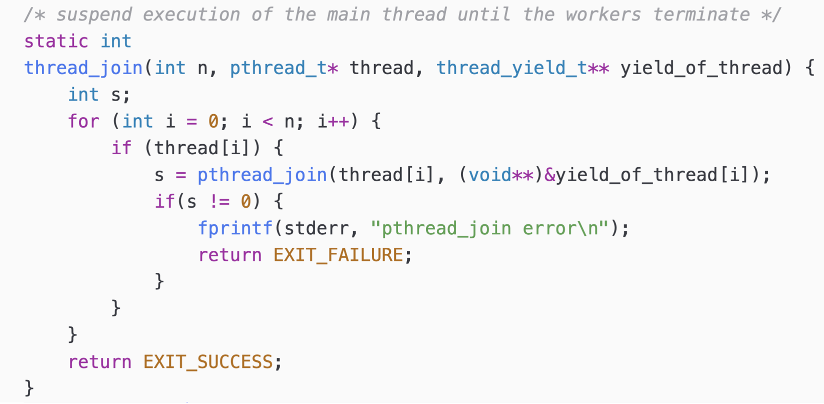
```c
static int create_thread_pool(int n, pthread_t** th, buffer_t *queue)
{
    int err;
    long int x;
    *th = (pthread_t*)malloc(sizeof(pthread_t)*n);
    pthread_t* thread = *th;
    char buffer[128], *end;

    assert(queue && n > 0);

    for (int i = 0; i < n; i++) {
        err = pthread_create(&thread[i], NULL, worker, queue);
        if (err) {
            fprintf(stderr, "%s: %s: unable to create thread %d: %d\n",
                progname, __func__, i, err);
            return EXIT_FAILURE;
        }
    }
    return EXIT_SUCCESS;
}
```

The read_numbers_from_stdin(...) function



```c
/* read numbers from standard input */
static void
read_numbers_from_stdin(buffer_t *queue)
{
    /* read numbers from the standard input */
    char tag[TAG_SIZE];
    unsigned long nat_num;

    while( fscanf(stdin,"%s%lu", tag, &nat_num) != EOF ) {
        enqueue(queue, tag, nat_num);
    }
    // Enter the critical section
    pthread_mutex_lock(&queue->mutex);
    // Critical section
    queue->flags |= BUFFER_CLOSED;
    // Exit the critical section
    pthread_mutex_unlock(&queue->mutex);
    pthread_cond_broadcast(&queue->full);
}
```

The thread_join(...) function



```
/* suspend execution of the main thread until the workers terminate */
static int
thread_join(int n, pthread_t* thread, thread_yield_t** yield_of_thread) {
    int s;
    for (int i = 0; i < n; i++) {
        if (thread[i]) {
            s = pthread_join(thread[i], (void**)&yield_of_thread[i]);
            if(s != 0) {
                fprintf(stderr, "pthread_join error\n");
                return EXIT_FAILURE;
            }
        }
    }
    return EXIT_SUCCESS;
}
```

The write_to_standard_output(...) function

```
/* display the output */
static void
write_to_standard_output(int nw, thread_yield_t** yield_of_thread)
{
    //
    for (int i = 0; i < nw; i++) {
        for(int j=0; j<yield_of_thread[i]->count; j++) {
            fprintf(stderr, "%s ", yield_of_thread[i]->completed_tasks_list[j]->tag);
            for(int k=0; k<yield_of_thread[i]->completed_tasks_list[j]->count; k++) {
                fprintf(stderr, "%lu ", yield_of_thread[i]->
                    completed_tasks_list[j]->factors[k]);
            }
            _NEW_LINE_
        }
    }
}
```

The free_heap_memory(...) function

```c
static void
free_heap_memory(int nw, pthread_t* thread, thread_yield_t** yield_of_thread) {
    /* free tag(s), factors array(s), completed_tasks_list array(s),
       yield_of_thread array(s), and thread array(s) */
    for (int i = 0; i < nw; i++) {
        for(int j=0; j<yield_of_thread[i]->count; j++) {
            free(yield_of_thread[i]->completed_tasks_list[j]->tag);
            yield_of_thread[i]->completed_tasks_list[j]->tag = NULL;
            free(yield_of_thread[i]->completed_tasks_list[j]->factors);
            yield_of_thread[i]->completed_tasks_list[j]->factors = NULL;
            free(yield_of_thread[i]->completed_tasks_list[j]); //
        }
        free(yield_of_thread[i]->completed_tasks_list);
        free(yield_of_thread[i]);
        yield_of_thread[i] = NULL;
    }
    free(thread); thread = NULL;
}
```

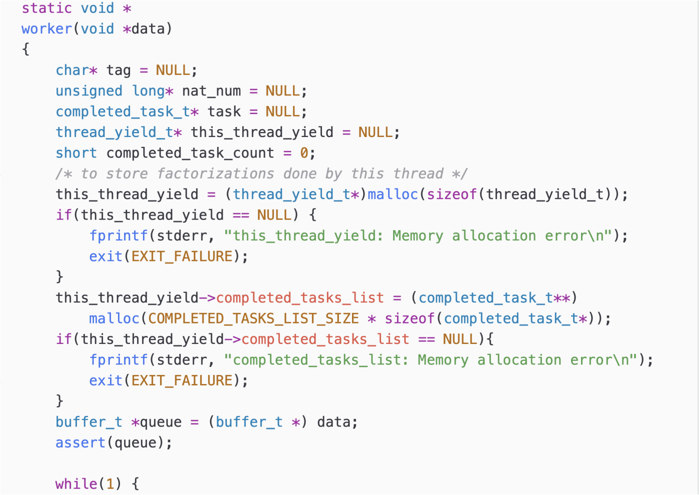
The enqueue(...) function

```c
/* place a (tag, number) pair in queue */
static void
enqueue(buffer_t *queue, char* tag, unsigned long nat_num)
{
    // Entr critical section
    pthread_mutex_lock(&queue->mutex);
    // Critical section
    while (queue->count == BUFFER_SIZE) {
        pthread_cond_wait(&queue->empty, &queue->mutex);
    }

    sprintf(queue->tag[queue->in], "%s", tag);
    queue->data[queue->in] = nat_num;
    queue->in = (queue->in + 1) % BUFFER_SIZE;
    queue->count++;

    pthread_cond_signal(&queue->full);
    // Exit critical section
    pthread_mutex_unlock(&queue->mutex);
}
```

The dequeue(...) function

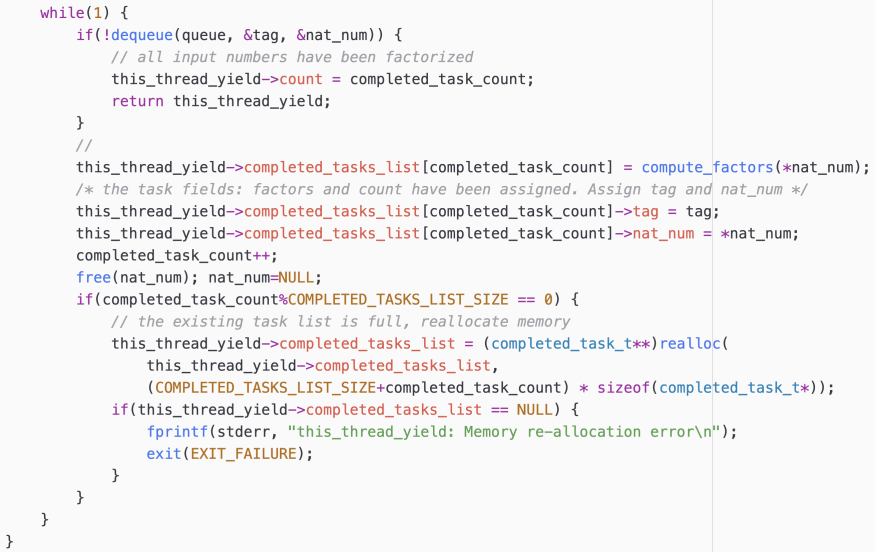
```c
/* pick a number from queue */
static int dequeue(buffer_t *queue, char** tag, unsigned long** nat_num)
{
    short tag_len = strlen(queue->tag[queue->out])+1;
    *tag = (char*)malloc(tag_len*sizeof(char));
    *nat_num = (unsigned long*)malloc(sizeof(unsigned long));
    if(tag==NULL || nat_num==NULL) exit(EXIT_FAILURE);
    /* Enter the critical section */
    pthread_mutex_lock(&queue->mutex);
    while (queue->count == 0) {
        if (queue->flags & BUFFER_CLOSED) {
            pthread_mutex_unlock(&queue->mutex);
            return DEQUEUE_FAILURE;
        }
        pthread_cond_wait(&queue->full, &queue->mutex);
    }
    //
    sprintf(*tag, "%s", queue->tag[queue->out]);
    **nat_num = queue->data[queue->out];
    queue->out = (queue->out + 1) % BUFFER_SIZE;
    queue->count--;

    pthread_cond_signal(&queue->empty);
    // Exit the critical section
    pthread_mutex_unlock(&queue->mutex);
    return DEQUEUE_SUCCESS;
}
```

The worker(...) function – part-I



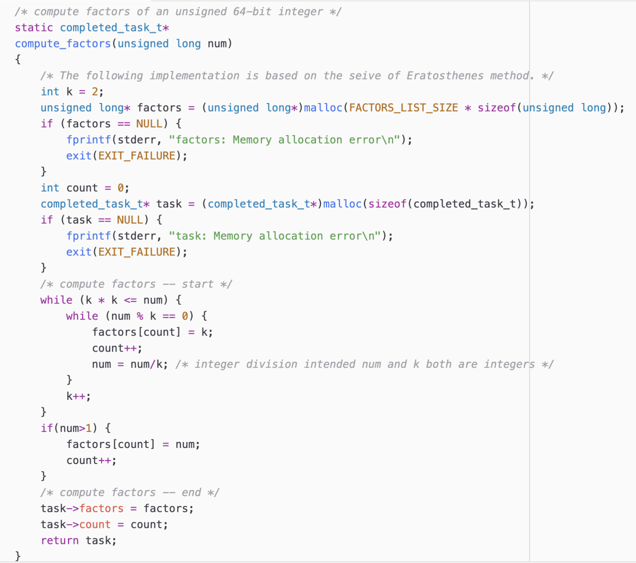
```
static void *
worker(void *data)
{
    char* tag = NULL;
    unsigned long* nat_num = NULL;
    completed_task_t* task = NULL;
    thread_yield_t* this_thread_yield = NULL;
    short completed_task_count = 0;
    /* to store factorizations done by this thread */
    this_thread_yield = (thread_yield_t*)malloc(sizeof(thread_yield_t));
    if(this_thread_yield == NULL) {
        fprintf(stderr, "this_thread_yield: Memory allocation error\n");
        exit(EXIT_FAILURE);
    }
    this_thread_yield->completed_tasks_list = (completed_task_t**)
        malloc(COMPLETED_TASKS_LIST_SIZE * sizeof(completed_task_t*));
    if(this_thread_yield->completed_tasks_list == NULL){
        fprintf(stderr, "completed_tasks_list: Memory allocation error\n");
        exit(EXIT_FAILURE);
    }
    buffer_t *queue = (buffer_t *) data;
    assert(queue);

    while(1) {
```

The worker(...) function – part-II



```c
    while(1) {
        if(!dequeue(queue, &tag, &nat_num)) {
            // all input numbers have been factorized
            this_thread_yield->count = completed_task_count;
            return this_thread_yield;
        }
        //
        this_thread_yield->completed_tasks_list[completed_task_count] = compute_factors(*nat_num);
        /* the task fields: factors and count have been assigned. Assign tag and nat_num */
        this_thread_yield->completed_tasks_list[completed_task_count]->tag = tag;
        this_thread_yield->completed_tasks_list[completed_task_count]->nat_num = *nat_num;
        completed_task_count++;
        free(nat_num); nat_num=NULL;
        if(completed_task_count%COMPLETED_TASKS_LIST_SIZE == 0) {
            // the existing task list is full, reallocate memory
            this_thread_yield->completed_tasks_list = (completed_task_t**)realloc(
                this_thread_yield->completed_tasks_list,
                (COMPLETED_TASKS_LIST_SIZE+completed_task_count) * sizeof(completed_task_t*));
            if(this_thread_yield->completed_tasks_list == NULL) {
                fprintf(stderr, "this_thread_yield: Memory re-allocation error\n");
                exit(EXIT_FAILURE);
            }
        }
    }
}
```

The compute_factors(...) function



```c
/* compute factors of an unsigned 64-bit integer */
static completed_task_t*
compute_factors(unsigned long num)
{
    /* The following implementation is based on the seive of Eratosthenes method. */
    int k = 2;
    unsigned long* factors = (unsigned long*)malloc(FACTORS_LIST_SIZE * sizeof(unsigned long));
    if (factors == NULL) {
        fprintf(stderr, "factors: Memory allocation error\n");
        exit(EXIT_FAILURE);
    }
    int count = 0;
    completed_task_t* task = (completed_task_t*)malloc(sizeof(completed_task_t));
    if (task == NULL) {
        fprintf(stderr, "task: Memory allocation error\n");
        exit(EXIT_FAILURE);
    }
    /* compute factors -- start */
    while (k * k <= num) {
        while (num % k == 0) {
            factors[count] = k;
            count++;
            num = num/k; /* integer division intended num and k both are integers */
        }
        k++;
    }
    if(num>1) {
        factors[count] = num;
        count++;
    }
    /* compute factors -- end */
    task->factors = factors;
    task->count = count;
    return task;
}
```

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Concluding Remarks

factorize – a multi-threaded program

- The use of thread pool pattern
- Thread synchronization primitives in **C**
  - POSIX Mutex Locks
  - POSIX Condition Variables
- Indicating end of standard input to the threads

A design flaw

- Larger **completed_tasks_list** with larger input (memory inefficient)
- **Solution:** maintain an output queue
- **Simplicity** (for demonstration) vs. Efficiency trade-off

Acknowledgment

The source code has been adapted from the basic **thread pool pattern** implementation available at Jacobs University source code repository for the course: Operating Systems. Although, significant changes have been made to the original source code to solve the given problem, the author of the program **factorize.c** duly acknowledges the contribution of the author(s) of the program **worker.c** available on the given link.