2023.1 Multicore Computing, Project #4

Problem 1

Course / Class:	Multicore Computing / Class 01
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1. Environment

- Hardware
  - CPU: Intel® Core™ i5-10400 CPU @ 2.90GHz
  - Memory: 16.0 GB, 2667MHz
  - GPU: NVIDIA GeForce GTX 1660 SUPER (1408 CUDA Cores, 6144MiB Memory)
- Software
  - Windows 10 Home
  - WSL2 (Windows Subsystem for Linux) – Ubuntu 20.04.6 LTS
  - CUDA Version: 12.1
  - NVIDIA Driver Version: 531.79
  - gcc: gcc (Ubuntu 9.4.0-1ubuntu1~20.04.1) 9.4.0
  - nvcc: V12.1.105, build cuda_12.1.r12.1/compiler.32688072_0

2. Compilation

1) openmp_ray.cpp

$ gcc -o openmp_ray openmp_ray.cpp -fopenmp -lm

2) cuda_ray.cu

$ nvcc -o cuda_ray cuda_ray.cu -O2

3. Execution

1) openmp_ray.cpp

$ ./openmp_ray [number_of_threads]

2) cuda_ray.cu

$ ./cuda_ray

4. Source Code

1) openmp_ray.cpp

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <time.h>
#include <math.h>
#include <omp.h>

#define SPHERES 20

#define rnd( x ) (x * rand() / RAND_MAX)
#define INF 2e10f
#define DIM 2048

struct Sphere {
    float   r,b,g;
    float   radius;
    float   x,y,z;
    float hit( float ox, float oy, float *n ) {
        float dx = ox - x;
        float dy = oy - y;
        if (dx*dx + dy*dy < radius*radius) {
            float dz = sqrtf( radius*radius - dx*dx - dy*dy );
            *n = dz / sqrtf( radius * radius );
            return dz + z;
        }
        return -INF;
    }
};

void kernel(int x, int y, Sphere* s, unsigned char* ptr)
{
    int offset = x + y*DIM;
    float ox = (x - DIM/2);
    float oy = (y - DIM/2);

    //printf("x:%d, y:%d, ox:%f, oy:%f\n",x,y,ox,oy);

    float r=0, g=0, b=0;
    float   maxz = -INF;
    for(int i=0; i<SPHERES; i++) {
        float   n;
        float   t = s[i].hit( ox, oy, &n );
        if (t > maxz) {
            float fscale = n;
            r = s[i].r * fscale;
            g = s[i].g * fscale;
            b = s[i].b * fscale;
            maxz = t;
        }
    }

    ptr[offset*4 + 0] = (int)(r * 255);
    ptr[offset*4 + 1] = (int)(g * 255);
    ptr[offset*4 + 2] = (int)(b * 255);
    ptr[offset*4 + 3] = 255;
}

void ppm_write(unsigned char* bitmap, int xdim,int ydim, FILE* fp)
{
    int i,x,y;
    fprintf(fp,"P3\n");
    fprintf(fp,"%d %d\n",xdim, ydim);
    fprintf(fp,"255\n");
    for (y=0;y<ydim;y++) {
        for (x=0;x<xdim;x++) {
            i=x+y*xdim;
            fprintf(fp,"%d %d %d ",bitmap[4*i],bitmap[4*i+1],bitmap[4*i+2]);
        }
        fprintf(fp,"\n");
```

```
    }
}

int main(int argc, char* argv[])
{
    int no_threads;
    // int option;
    int x,y;
    unsigned char* bitmap;
    double start_time, end_time;

    srand(time(NULL));

    if (argc!=2) {
        printf("> a.out [option] \n");
        printf("[option] 1~32: OpenMP using 1~32 threads\n");
        printf("for example, '> a.out 8' means executing OpenMP with 8 threads\n");
        exit(0);
    }
    FILE* fp = fopen("result.ppm","w");

    no_threads=atoi(argv[1]);

    Sphere *temp_s = (Sphere*)malloc( sizeof(Sphere) * SPHERES );
    for (int i=0; i<SPHERES; i++) {
        temp_s[i].r = rnd( 1.0f );
        temp_s[i].g = rnd( 1.0f );
        temp_s[i].b = rnd( 1.0f );
        temp_s[i].x = rnd( 2000.0f ) - 1000;
        temp_s[i].y = rnd( 2000.0f ) - 1000;
        temp_s[i].z = rnd( 2000.0f ) - 1000;
        temp_s[i].radius = rnd( 200.0f ) + 40;
    }

    bitmap=(unsigned char*)malloc(sizeof(unsigned char)*DIM*DIM*4);

    // Set number of threads
    omp_set_num_threads(no_threads);

    // Get start time
    start_time = omp_get_wtime();

    // Parallelize the nested for-loop
    #pragma omp parallel for default(shared) private(x,y) schedule(dynamic)
    for (x=0;x<DIM;x++)
        for (y=0;y<DIM;y++) kernel(x,y,temp_s,bitmap);

    // Get end time
    end_time = omp_get_wtime();

    ppm_write(bitmap,DIM,DIM,fp);

    fclose(fp);
    free(bitmap);
    free(temp_s);

    // Print execution time
    printf("OpenMP (%d threads) ray tracing: %.3lf sec\n", no_threads, end_time-start_time);
    printf("[result.ppm] was generated\n");

    return 0;
}
```

2) cuda_ray.cu

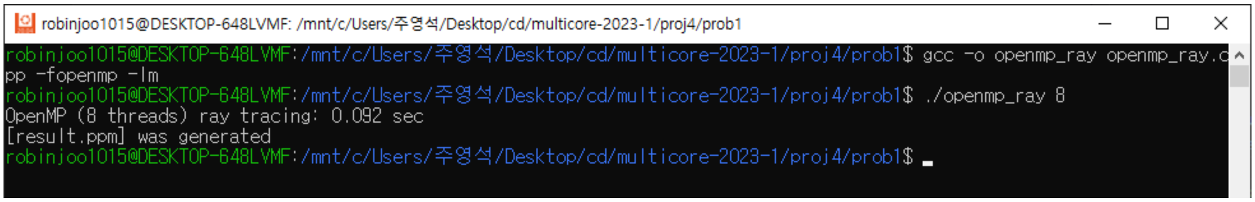
```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
#include <time.h>
#include <math.h>

#define SPHERES 20

#define rnd( x ) (x * rand() / RAND_MAX)
#define INF 2e10f
#define DIM 2048

struct Sphere {
    float   r,b,g;
    float   radius;
    float   x,y,z;
    // Set hit method to be executed on device
    __device__ float hit( float ox, float oy, float *n ) {
        float dx = ox - x;
        float dy = oy - y;
        if (dx*dx + dy*dy < radius*radius) {
            float dz = sqrtf( radius*radius - dx*dx - dy*dy );
            *n = dz / sqrtf( radius * radius );
            return dz + z;
        }
        return -INF;
    }
};

// Set kernel method to be executed on device
__global__ void kernel(Sphere* s, unsigned char* ptr)
{
    // Calculate x and y from built-in variables
    int x = blockIdx.x * blockDim.x + threadIdx.x;
    int y = blockIdx.y * blockDim.y + threadIdx.y;
    int offset = x + y*DIM;
    float ox = (x - DIM/2);
    float oy = (y - DIM/2);

    //printf("x:%d, y:%d, ox:%f, oy:%f\n",x,y,ox,oy);

    float r=0, g=0, b=0;
    float   maxz = -INF;
    for(int i=0; i<SPHERES; i++) {
        float   n;
        float   t = s[i].hit( ox, oy, &n );
        if (t > maxz) {
            float fscale = n;
            r = s[i].r * fscale;
            g = s[i].g * fscale;
            b = s[i].b * fscale;
            maxz = t;
        }
    }

    ptr[offset*4 + 0] = (int)(r * 255);
    ptr[offset*4 + 1] = (int)(g * 255);
    ptr[offset*4 + 2] = (int)(b * 255);
    ptr[offset*4 + 3] = 255;
}

void ppm_write(unsigned char* bitmap, int xdim,int ydim, FILE* fp)
{
    int i,x,y;
    fprintf(fp,"P3\n");
    fprintf(fp,"%d %d\n",xdim, ydim);
    fprintf(fp,"255\n");
    for (y=0;y<ydim;y++) {
        for (x=0;x<xdim;x++) {
            i=x+y*xdim;
            fprintf(fp,"%d %d %d ",bitmap[4*i],bitmap[4*i+1],bitmap[4*i+2]);
```

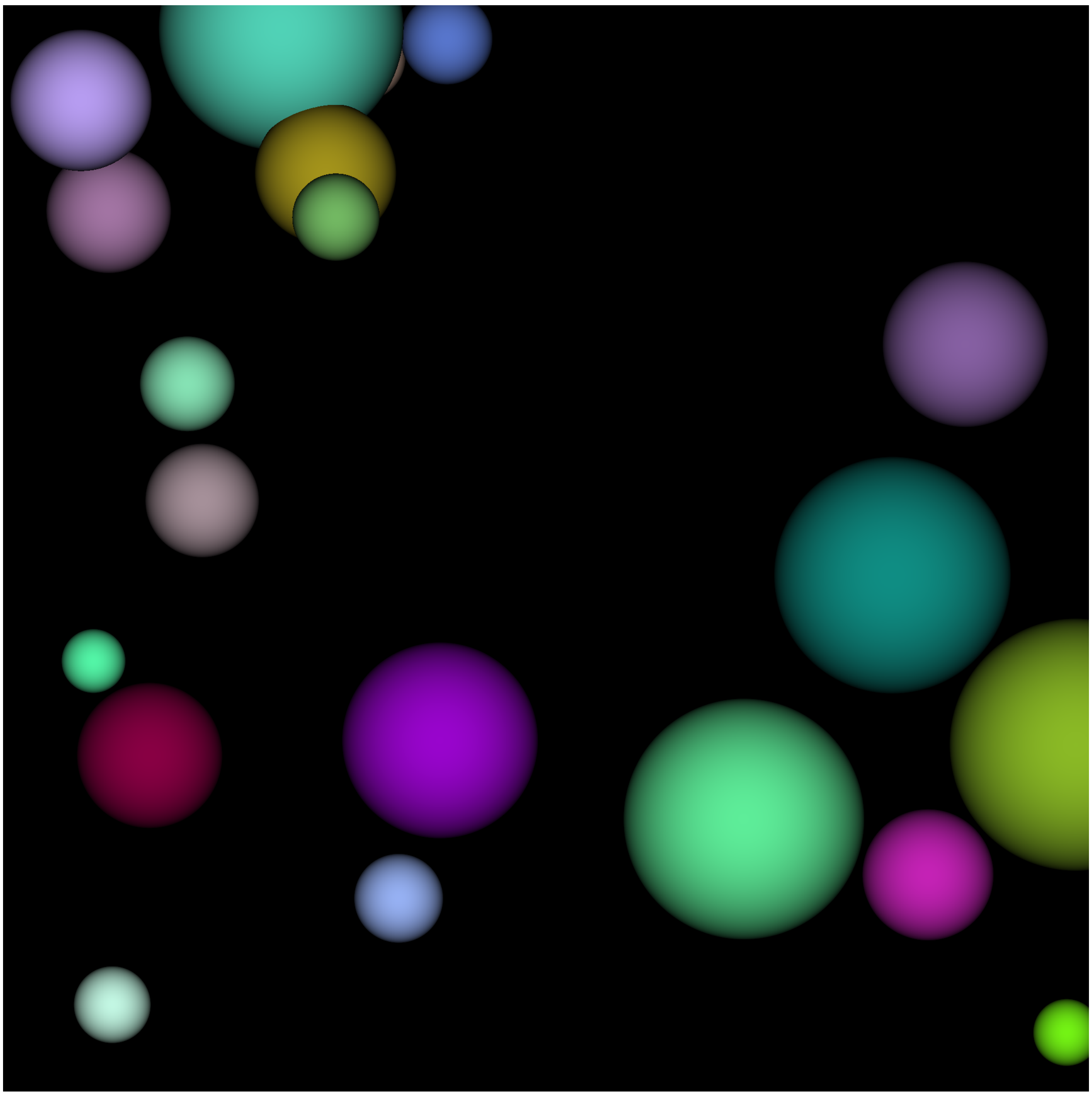
```
        }
        fprintf(fp,"\n");
    }
}

int main(int argc, char* argv[])
{
    unsigned char *bitmap;
    unsigned char *device_bitmap; // Bitmap on device
    Sphere *temp_s;
    Sphere *device_temp_s; // Sphere on device
    clock_t start_time, end_time;

    srand(time(NULL));

    FILE *fp = fopen("result.ppm","w");

    temp_s = (Sphere *)malloc(sizeof(Sphere) * SPHERES);
    // Allocate sphere memory on device
    cudaMalloc((void **)&device_temp_s, sizeof(Sphere) * SPHERES);
    for (int i=0; i<SPHERES; i++) {
        temp_s[i].r = rnd( 1.0f );
        temp_s[i].g = rnd( 1.0f );
        temp_s[i].b = rnd( 1.0f );
        temp_s[i].x = rnd( 2000.0f ) - 1000;
        temp_s[i].y = rnd( 2000.0f ) - 1000;
        temp_s[i].z = rnd( 2000.0f ) - 1000;
        temp_s[i].radius = rnd( 200.0f ) + 40;
    }

    bitmap=(unsigned char *)malloc(sizeof(unsigned char) * DIM * DIM * 4);
    // Allocate bitmap memory on device
    cudaMalloc((void **)&device_bitmap, sizeof(unsigned char) * DIM * DIM * 4);

    // Copy generated spheres to device
    cudaMemcpy(device_temp_s, temp_s, sizeof(Sphere) * SPHERES, cudaMemcpyHostToDevice);

    // Set blocks and threads
    dim3 blocks(DIM / 32, DIM / 32, 1);
    dim3 threads(32, 32, 1);

    start_time = clock();

    // Execute kernel function
    kernel<<<blocks, threads>>>(device_temp_s, device_bitmap);
    // Wait for device
    cudaDeviceSynchronize();

    end_time = clock();

    // Copy calculated spheres from device
    cudaMemcpy(bitmap, device_bitmap, sizeof(unsigned char) * DIM * DIM * 4, cudaMemcpyDeviceToHost);

    ppm_write(bitmap, DIM, DIM, fp);

    // Free device memory
    cudaFree(device_temp_s);
    cudaFree(device_bitmap);

    free(temp_s);
    free(bitmap);
    fclose(fp);

    // Print execution time
    printf("CUDA ray tracing: %.3lf sec\n", (end_time-start_time)/(double)1000);
    printf("[result.ppm] was generated\n");

    return 0;
}
```

5. Output Results

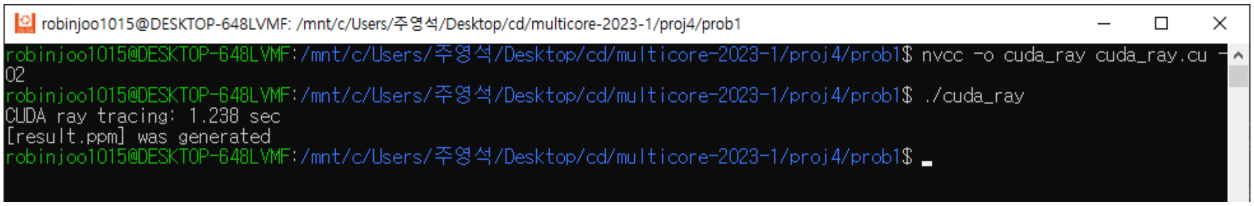
result.ppm was converted into result.png by ffmpeg ($ *ffmpeg -i result.ppm result.png*)

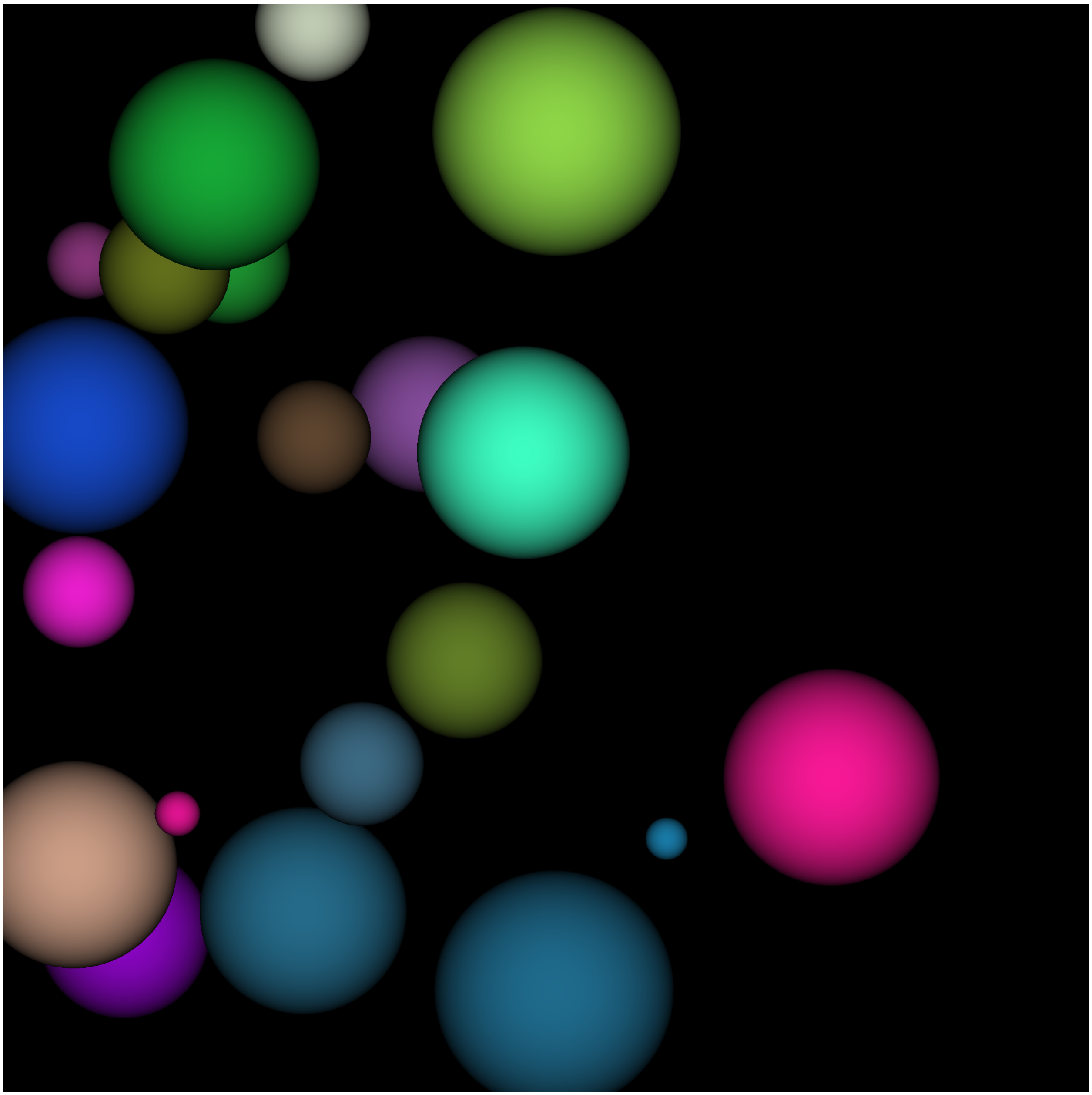
1) openmp_ray





2) cuda_ray


robinjoo1015@DESKTOP-648LVMF: /mnt/c/Users/주영석/Desktop/cd/multicore-2023-1/proj4/prob1
robinjoo1015@DESKTOP-648LVMF:/mnt/c/Users/주영석/Desktop/cd/multicore-2023-1/proj4/prob1$ nvcc -o cuda_ray cuda_ray.cu -
02
robinjoo1015@DESKTOP-648LVMF:/mnt/c/Users/주영석/Desktop/cd/multicore-2023-1/proj4/prob1$ ./cuda_ray
CUDA ray tracing: 1.238 sec
[result.ppm] was generated
robinjoo1015@DESKTOP-648LVMF:/mnt/c/Users/주영석/Desktop/cd/multicore-2023-1/proj4/prob1$



6. Experimental Results

1) OpenMP

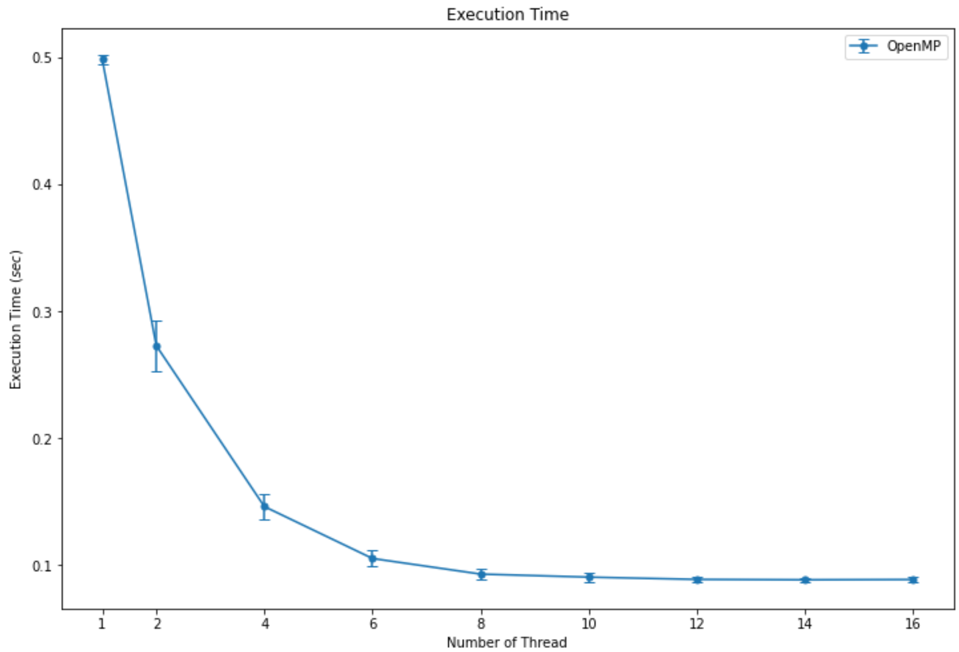


Figure 1. Error Bar Graph showing Execution Time of OpenMP with Various Numbers of Threads (10-Fold).

Table 1. Table showing Average Execution Time of OpenMP with Various Numbers of Threads (10-Fold).

Number of Threads	1	2	4	6	8	10	12	14	16
Execution Time (sec)	0.4987	0.2731	0.1463	0.1054	0.0931	0.0907	0.0889	0.0886	0.0888

OpenMP raytracing implementation was tested using 1, 2, 4, 6, 8, 10, 12, 14, and 16 threads. When the number of threads increases, execution time decreases significantly by utilizing multiple CPU cores. The execution time converges when the number of threads is about 10. This is because the physical core is limited to 12 cores.

2) CUDA

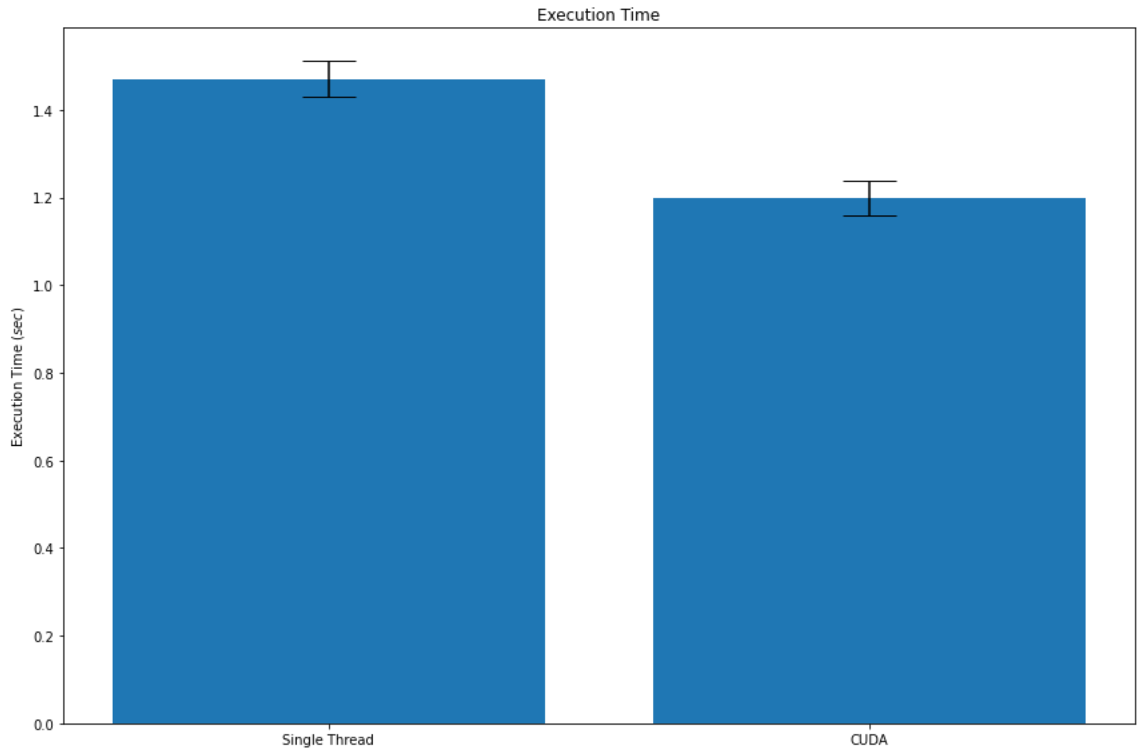


Figure 2. Bar Graph showing Execution Times of Single Thread and CUDA Implementation (10-Fold).

CUDA version of raytracing was implemented by utilizing CUDA functionalities. The core 'kernel' function was executed in multiple GPU cores parallelly. The number of threads in a block was set as 32 * 32 * 1, where the number of blocks in a grid was set as (DIM/32) * (DIM/32) * 1, dividing total DIM * DIM calculations.

CUDA raytracing implementation was tested by comparing execution time with the single thread version. Compared to the single thread version, the execution time of the CUDA version was shorter, where the single thread version took 1.4707 seconds, and the CUDA version took 1.1994 seconds on average.