CSC612M - G01 - MP2

Members:
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Google Collab Source Code: Link

I. C++ version of the Kernel

A. The C++ version of the kernel takes in the same parameter structure as the CUDA kernel. The whole parameter structure is implemented below:

```
struct GaussianParams{
  int width;
  int height;
  int radius;
  float std_dev;

  float* in_r;
  float* in_g;
  float* in_b;

  float* out_r;
  float* out_g;
  float* out_b;
};
```

This structure takes in the image's dimensions, the Gaussian function parameters radius and standard deviation, the input image's color data split into 3 arrays for the R, G, and B channels, and the 3 arrays for the output color split in a similar way.

B. The main operation of the Gaussian function is the ComputeWeight function. Its corresponding C++ implementation is found below:

```
float ComputeWeight(float center_x, float center_y, float curr_x, float curr_y, float std_dev){
  float x = center_x - curr_x;
  float y = center_y - curr_y;

  float x2 = x*x;
  float y2 = y*y;
  float std2 = std_dev*std_dev;

  float e_pow = (x2 + y2) / (2* std2) * -1;
  float e = std::exp(e_pow);

  float frac = 1 / (std::sqrt(2 * M_PI * std2));

  return frac * e;
}
```

C. The Gaussian function implementation loops through all of the pixels of the input image passed through the input structure.

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```
void GaussianBlur(GaussianParams *g_param){
  std::cout << "Image dimensions: " << g_param->width << "x" << g_param->height << std::endl;

  for (int curr_y = 0; curr_y < g_param->height; ++curr_y) {
      for (int curr_x = 0; curr_x < g_param->width; ++curr_x) {
```

After, it checks if adding in the radius will make the function access invalid pixels or locations such as the corners and edges. It does this by running the following lines to clamp the boundary window.

```
float minX = std::max(curr_x - g_param->radius, 0);
float maxX = std::min(curr_x + g_param->radius, g_param->width);

float minY = std::max(curr_y - g_param->radius, 0);
float maxY = std::min(curr_y + g_param->radius, g_param->height);
```

It will then loop through the given range, getting the weight of each pixel using the function above and multiplying said weight to the color of the pixel.

```
//Compute for the summation of colors here
for(int y = minY; y < maxY; y++){
  for(int x = minX; x < maxX; x++){
    float weight = ComputeWeight(curr_x, curr_y, x, y, g_param->std_dev);
    int curr_index = y * g_param->width + x;

    totR += g_param->in_r[curr_index] * weight;
    totG += g_param->in_g[curr_index] * weight;
    totB += g_param->in_b[curr_index] * weight;

    //For normalization later
    baseMax += 1.f *weight;
  }
}
```

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Finally, we normalize the resulting colors and assign them to the respective output pixel.

```
//Normalize the colors here
float ceilVal = 1.f / baseMax;

totR *= ceilVal;
totG *= ceilVal;
totB *= ceilVal;
//////////////////////////

g_param->out_r[index] = totR;
g_param->out_g[index] = totG;
g_param->out_b[index] = totB;
```

II. **CUDA Kernel**

a. **Grid-Stride Loop**: The pure version without prefetching or page-creation optimizations. The goal of this baseline is to establish a clear performance and correctness reference before applying more advanced optimizations. The base GSL kernel assigns each thread an index, and that thread processes multiple pixels by incrementing by the number of active threads. There are no optimizations yet, no shared memory, no prefetch, no caching tricks. It directly loads from global memory for every neighbor pixel, computes Gaussian weights, accumulates RGB values, and normalizes. The Grid-Stride Loop pattern makes our kernel scalable. Instead of having each thread process just one pixel, every thread loops through the image with a fixed stride. This ensures high occupancy and makes the kernel independent of image dimensions.

The image below shows the core of the GSL. The kernel computes the global index of each thread and then loops across the image using a constant stride equal to the total number of threads. Each thread starts at its unique index and processes every stride-th pixel. This ensures scalability regardless of image size. No matter the resolution, 512, 1024, or 2048, the kernel remains stable and evenly balanced:

```
int index = blockIdx.x * blockDim.x + threadIdx.x;
int stride = blockDim.x * gridDim.x;
int pixelCount = g_param->width * g_param->height;

for (int i = index; i < pixelCount; i += stride){
```

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The image below shows the Gaussian function implemented on the GPU. It requires computing the exponential for every neighbor pixel. Because we're using no precomputed kernel and no caching, this baseline version performs many redundant operations, which later optimizations will aim to reduce:

```
float e_pow = (x*x + y*y) / (2.0f * std_dev * std_dev) * -1.0f;
float e = expf(e_pow);
float frac = 1.0f / sqrtf(2.0f * M_PIf * (std_dev * std_dev));

return frac * e;
```

The image below shows the brute-force convolution. For each pixel, we traverse all neighbors within the radius. Every RGB channel is fetched from global memory every loop iteration. This is the main performance bottleneck and the reason prefetching and page creation will later provide speedups:

```
for (int y = minY; y < maxY; y++){
  for (int x = minX; x < maxX; x++){
    float weight = ComputeWeight(curr_x, curr_y, (float)x, (float)y, g_param->std_dev);
    int idx = y * g_param->width + x;

    totR += g_param->in_r[idx] * weight;
    totG += g_param->in_g[idx] * weight;
    totB += g_param->in_b[idx] * weight;

    baseMax += weight;
```

The image below shows our boundary handling. We clamp the window so threads never read outside the image, avoiding invalid memory accesses:

```
int minX = max(curr_x - g_param->radius, 0);
int maxX = min(curr_x + g_param->radius + 1, g_param->width);

int minY = max(curr_y - g_param->radius, 0);
int maxY = min(curr_y + g_param->radius + 1, g_param->height);
```

The image below shows how we performed normalization. After summing weighted values, we divide by the total weight to normalize the pixel. This ensures the pixel remains within a valid intensity range and preserves color correctness. This part is crucial in validating the result later using RMSE comparisons:

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```
if (baseMax > 1e-6f) {
  float ceilVal = 1.0f / baseMax;
  g_param->out_r[i] = totR * ceilVal;
  g_param->out_g[i] = totG * ceilVal;
  g_param->out_b[i] = totB * ceilVal;
} else {
  g_param->out_r[i] = g_param->in_r[i];
  g_param->out_g[i] = g_param->in_g[i];
  g_param->out_b[i] = g_param->in_b[i];
}
```

Lastly, the image below shows our validation. To ensure correctness, we compare the GPU output against a reference CPU image using RMSE. This gives us a numeric measure of accuracy. This baseline implementation is essential because all further optimizations must match its output while improving performance:

```
cv::Mat compImage = cv::imread(compPath, cv::IMREAD_COLOR);
cv::Mat outputImage = cv::imread("512x512_outputImage_cuda_a.jpg", cv::IMREAD_COLOR);

std::cout << "Validation from image" << std::endl;
auto rmse = RSME(gaussianParams, compImage);
std::cout << "RMSE from image: " << rmse << std::endl;

std::cout << "Validation from file" << std::endl;
auto rmse2 = RSME_FromFile(gaussianParams, "output512.csv");
std::cout << "RMSE from file " << rmse2 << std::endl;
```

b. Grid-Stride Loop with Prefetch

This implementation introduces the use of Data Prefetching. The features are the same as those in the GSL implementation, except for the use of cudaMemPrefetchAsync, which tells the CUDA runtime to move the gaussianParams to memory space asynchronously.

The image below is a code snippet of the prefetch data from CPU-GPU i that executes before the kernel launch, which prepares the data for the device.

```
// Prefetch data from CPU-GPU
cudaMemPrefetchAsync(gaussianParams->in_r,array_byte_size, device, NULL);
cudaMemPrefetchAsync(gaussianParams->in_g,array_byte_size, device, NULL);
cudaMemPrefetchAsync(gaussianParams->in_b,array_byte_size, device, NULL);
```

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The image below is a code snippet of the prefetch data from GPU to CPU that prepares the output data for the host and validation functions.

```
// Prefetch data from GPU-CPU
cudaMemPrefetchAsync(gaussianParams->out_r,array_byte_size, cudaCpuDeviceId, NULL);
cudaMemPrefetchAsync(gaussianParams->out_g,array_byte_size, cudaCpuDeviceId, NULL);
cudaMemPrefetchAsync(gaussianParams->out_b,array_byte_size, cudaCpuDeviceId, NULL);
```

c. Grid-Stride Loop with Prefetch and Page Creation

With Page Creation, we are reducing the CPU and GPU page faults by prefetching blank data from both the CPU and GPU page memories. This implementation appends the GSL + Prefetch Kernel, and similar to Prefetch, it uses the CUDA instruction: cudaMemPrefetchAsync. We perform this to our parameters in the gaussianParams class object.

The image below is a code snippet of prefetching blank data from both CPU and GPU page memories.

```
// Page Creation
//"prefetch data" to create CPU page memory
cudaMemPrefetchAsync(gaussianParams->in_r,array_byte_size, cudaCpuDeviceId, NULL);
cudaMemPrefetchAsync(gaussianParams->in_g,array_byte_size, cudaCpuDeviceId, NULL);
cudaMemPrefetchAsync(gaussianParams->in_b,array_byte_size, cudaCpuDeviceId, NULL);

//"prefetch data" to create GPU page memory
cudaMemPrefetchAsync(gaussianParams->out_r,array_byte_size, device, NULL);
cudaMemPrefetchAsync(gaussianParams->out_g,array_byte_size, device, NULL);
cudaMemPrefetchAsync(gaussianParams->out_b,array_byte_size, device, NULL);
```

d. Grid-Stride Loop with Prefetch, Page Creation, and Memory Advise

With Memory Advise, we are further reducing the CPU and GPU page faults by advising CUDA with the memory pointer. This implementation appends the GSL, Prefetch, and Page Creation Kernel. It uses the CUDA instruction: cudaMemAdvise. We perform this to our “in” parameters in the gaussianParams class object.

The image below is a code snippet where the cudaMemAdvice is implemented.

```
// Memory Advise
 cudaMemAdvise(gaussianParams->in_r, array_byte_size, cudaMemAdviseSetPreferredLocation, cudaCpuDeviceId);
 cudaMemAdvise(gaussianParams->in_r, array_byte_size, cudaMemAdviseSetReadMostly, cudaCpuDeviceId);
 cudaMemAdvise(gaussianParams->in_g, array_byte_size, cudaMemAdviseSetPreferredLocation, cudaCpuDeviceId);
 cudaMemAdvise(gaussianParams->in_g, array_byte_size, cudaMemAdviseSetReadMostly, cudaCpuDeviceId);
 cudaMemAdvise(gaussianParams->in_b, array_byte_size, cudaMemAdviseSetPreferredLocation, cudaCpuDeviceId);
 cudaMemAdvise(gaussianParams->in_b, array_byte_size, cudaMemAdviseSetReadMostly, cudaCpuDeviceId);
```

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- Tallied the results for the versions above.
    - Sample Output:
        - Gaussian Blur Parameters:
            - Radius: 20
            - Standard Deviation: 20

Original Image (e.g., 512 x 512)	**Processed Image (e.g., 512 x 512)**
	

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C++ Kernel Execution

- C++ Kernel Execution (512 x 512):

```
Image loaded successfully!
Image dimensions: 512x512
Array size: 1048576
Initial Time Elapsed: 0 ms
Will Process Image
Image dimensions: 512x512
Run 0 Execution Time: 11955.1 ms
Donee Process Image
C Kernel output written to: output512.csv
Image Saved
Average Execution Time (10 Runs): 11955.1 ms
```

- C++ Kernel Execution (1024 x 1024):

```
Image loaded successfully!
Image dimensions: 1024x1024
Array size: 4194304
Initial Time Elapsed: 0 ms
Will Process Image
Image dimensions: 1024x1024
Run 0 Execution Time: 50536.7 ms
Donee Process Image
C Kernel output written to: output1024.csv
Image Saved
Average Execution Time (10 Runs): 50536.7 ms
```

- C++ Kernel Execution (2048 x 2048):

```
Image loaded successfully!
Image dimensions: 2048x2048
Array size: 16777216
Initial Time Elapsed: 0 ms
Will Process Image
Image dimensions: 2048x2048
Run 0 Execution Time: 202619 ms
Donee Process Image
C Kernel output written to: output2048.csv
Image Saved
Average Execution Time (10 Runs): 202619 ms
```

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CUDA GSL Execution

- GSL Execution (512 x 512):

```
Image loaded successfully!
Image dimensions: 512x512
Will Process Image
Finished processing.
512x512_outputImage.jpg saved.
Validation from image
MSE: 2.3412e-05
RMSE from image: 0.00483859
Validation from file
MSE: 1.06483e-05
RMSE from file 0.00326317
==27095== Profiling application: ./imageLoad
==27095== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  77.234ms        10  7.7234ms  7.6210ms  8.5657ms  GaussianBlur(GaussianParams*)
      API calls:   58.59%  110.47ms         7  15.781ms  2.4390us  110.38ms  cudaMallocManaged
                   40.92%  77.147ms         1  77.147ms  77.147ms  77.147ms  cudaDeviceSynchronize
                    0.25%  475.17us         7  67.881us  10.530us  105.33us  cudaFree
                    0.15%  288.24us        10  28.823us  5.0800us  188.20us  cudaLaunchKernel
                    0.08%  146.38us       114  1.2840us     102ns  63.660us  cuDeviceGetAttribute
                    0.01%  12.165us         1  12.165us  12.165us  12.165us  cuDeviceGetName
                    0.00%  5.4110us         1  5.4110us  5.4110us  5.4110us  cuDeviceGetPCIBusId
                    0.00%  1.4640us         3     488ns     135ns  1.0790us  cuDeviceGetCount
                    0.00%     841ns         2     420ns     206ns     635ns  cuDeviceGet
                    0.00%     600ns         1     600ns     600ns     600ns  cuModuleGetLoadingMode
                    0.00%     587ns         1     587ns     587ns     587ns  cuDeviceTotalMem
                    0.00%     465ns         1     465ns     465ns     465ns  cudaGetLastError
                    0.00%     216ns         1     216ns     216ns     216ns  cuDeviceGetUuid

==27095== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
      37  110.70KB  4.0000KB  0.9961MB  4.000000MB  441.0130us  Host To Device
      31  101.16KB  4.0000KB  512.00KB  3.062500MB  302.5540us  Device To Host
      24         -         -         -           -  2.066576ms  Gpu page fault groups
Total CPU Page faults: 30
```

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- GSL Execution (1024 x 1024):

```
Image loaded successfully!
Image dimensions: 1024x1024
Will Process Image
Finished processing.
1024x1024_outputImage.jpg saved.
Validation from image
MSE: 1.5554e-05
RMSE from image: 0.00394385
Validation from file
MSE: 4.27375e-06
RMSE from file 0.00206731
==26027== Profiling application: ./imageLoad
==26027== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  245.84ms        10  24.584ms  14.735ms  32.704ms  GaussianBlur(GaussianParams*)
      API calls:   70.13%  245.84ms         1  245.84ms  245.84ms  245.84ms  cudaDeviceSynchronize
                   29.42%  103.14ms         7  14.735ms  10.296us  103.03ms  cudaMallocManaged
                    0.34%  1.1788ms         7  168.40us  76.044us  255.89us  cudaFree
                    0.06%  211.97us        10  21.196us  3.4660us  174.49us  cudaLaunchKernel
                    0.04%  143.74us       114  1.2600us     104ns  60.822us  cuDeviceGetAttribute
                    0.00%  14.293us         1  14.293us  14.293us  14.293us  cuDeviceGetName
                    0.00%  4.8830us         1  4.8830us  4.8830us  4.8830us  cuDeviceGetPCIBusId
                    0.00%  1.2890us         3     429ns     122ns     901ns  cuDeviceGetCount
                    0.00%     814ns         2     407ns     165ns     649ns  cuDeviceGet
                    0.00%     517ns         1     517ns     517ns     517ns  cuDeviceTotalMem
                    0.00%     515ns         1     515ns     515ns     515ns  cuModuleGetLoadingMode
                    0.00%     448ns         1     448ns     448ns     448ns  cudaGetLastError
                    0.00%     256ns         1     256ns     256ns     256ns  cuDeviceGetUuid

==26027== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
      74  166.92KB  4.0000KB  0.9961MB  12.06250MB  1.239462ms  Host To Device
      74  166.92KB  4.0000KB  0.9961MB  12.06250MB  1.084800ms  Device To Host
      46         -         -         -           -  5.250723ms  Gpu page fault groups
Total CPU Page faults: 74
```

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- GSL Execution (2048 x 2048):

```
Image loaded successfully!
Image dimensions: 2048x2048
Will Process Image
Finished processing.
2048x2048_outputImage_cuda_a.jpg saved.
Validation from image
MSE: 1.35444e-05
RMSE from image: 0.00368026
Validation from file
MSE: 2.09942e-06
RMSE from file 0.00144894
==23876== Profiling application: ./imageLoad
==23876== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  711.45ms        10  71.145ms  60.339ms  131.66ms  GaussianBlur(GaussianParams*)
      API calls:   85.93%  711.41ms         1  711.41ms  711.41ms  711.41ms  cudaDeviceSynchronize
                   13.34%  110.42ms         7  15.774ms  8.0620us  110.25ms  cudaMallocManaged
                    0.68%  5.6263ms         7  803.76us  91.580us  1.0365ms  cudaFree
                    0.03%  259.95us        10  25.994us  5.3040us  203.56us  cudaLaunchKernel
                    0.02%  145.22us       114  1.2730us     106ns  64.089us  cuDeviceGetAttribute
                    0.00%  14.255us         1  14.255us  14.255us  14.255us  cuDeviceGetName
                    0.00%  5.1980us         1  5.1980us  5.1980us  5.1980us  cuDeviceGetPCIBusId
                    0.00%  1.6700us         3     556ns     208ns  1.1870us  cuDeviceGetCount
                    0.00%     848ns         2     424ns     212ns     636ns  cuDeviceGet
                    0.00%     699ns         1     699ns     699ns     699ns  cuDeviceTotalMem
                    0.00%     513ns         1     513ns     513ns     513ns  cudaGetLastError
                    0.00%     348ns         1     348ns     348ns     348ns  cuModuleGetLoadingMode
                    0.00%     281ns         1     281ns     281ns     281ns  cuDeviceGetUuid

==23876== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
     299  164.60KB  4.0000KB  0.9961MB  48.06250MB  4.972040ms  Host To Device
     290  169.71KB  4.0000KB  0.9961MB  48.06250MB  4.291386ms  Device To Host
     183         -         -         -           -  21.00900ms  Gpu page fault groups
Total CPU Page faults: 290
```

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CUDA GSL with Prefetch Execution

- CUDA GSL - Prefetch Execution (512 x 512):

```
Image loaded successfully!
Image dimensions: 512x512
Array size: 1048576
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 2.3412e-05
RMSE from image: 0.00483859
Validation from file
MSE: 1.06483e-05
RMSE from file 0.00326317
==23637== Profiling application: ./imageLoad
==23637== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  77.206ms        10  7.7206ms  7.6546ms  8.2211ms  GaussianBlur(GaussianParams*)
      API calls:   55.84%  100.52ms         7  14.360ms  2.4640us  100.41ms  cudaMallocManaged
                   42.84%  77.108ms         1  77.108ms  77.108ms  77.108ms  cudaDeviceSynchronize
                    0.73%  1.3060ms         8  163.25us  60.170us  487.48us  cudaMemPrefetchAsync
                    0.30%  548.49us         7  78.355us  14.221us  113.37us  cudaFree
                    0.19%  349.79us        10  34.979us  5.2060us  236.64us  cudaLaunchKernel
                    0.08%  149.70us       114  1.3130us     102ns  66.655us  cuDeviceGetAttribute
                    0.01%  12.562us         1  12.562us  12.562us  12.562us  cuDeviceGetName
                    0.00%  6.1240us         1  6.1240us  6.1240us  6.1240us  cudaGetDevice
                    0.00%  4.8690us         1  4.8690us  4.8690us  4.8690us  cuDeviceGetPCIBusId
                    0.00%  1.6070us         3     535ns     133ns  1.1640us  cuDeviceGetCount
                    0.00%     843ns         2     421ns     182ns     661ns  cuDeviceGet
                    0.00%     564ns         1     564ns     564ns     564ns  cudaGetLastError
                    0.00%     517ns         1     517ns     517ns     517ns  cuDeviceTotalMem
                    0.00%     322ns         1     322ns     322ns     322ns  cuModuleGetLoadingMode
                    0.00%     278ns         1     278ns     278ns     278ns  cuDeviceGetUuid

==23637== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
      21  244.19KB  4.0000KB  1.0039MB  5.007813MB  482.6440us  Host To Device
       7  586.86KB  4.0000KB  1.0000MB  4.011719MB  330.6160us  Device To Host
      22         -         -         -           -  1.760440ms  Gpu page fault groups
Total CPU Page faults: 17
```

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- CUDA GSL - Prefetch Execution (1024 x 1024):

```
Image loaded successfully!
Image dimensions: 1024x1024
Array size: 4194304
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 1.5554e-05
RMSE from image: 0.00394385
Validation from file
MSE: 4.27375e-06
RMSE from file 0.00206731
==23432== Profiling application: ./imageLoad
==23432== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  248.67ms        10  24.867ms  21.502ms  32.184ms  GaussianBlur(GaussianParams*)
      API calls:   70.31%  248.59ms         1  248.59ms  248.59ms  248.59ms  cudaDeviceSynchronize
                   27.86%  98.508ms         7  14.073ms  8.7820us  98.394ms  cudaMallocManaged
                    0.85%  3.0022ms        10  300.22us  5.3220us  2.8979ms  cudaLaunchKernel
                    0.66%  2.3187ms         8  289.84us  6.4600us  544.67us  cudaMemPrefetchAsync
                    0.27%  942.07us         7  134.58us  55.213us  201.18us  cudaFree
                    0.05%  178.88us       114  1.5690us     106ns  93.179us  cuDeviceGetAttribute
                    0.00%  12.233us         1  12.233us  12.233us  12.233us  cuDeviceGetName
                    0.00%  5.6870us         1  5.6870us  5.6870us  5.6870us  cuDeviceGetPCIBusId
                    0.00%  4.3200us         1  4.3200us  4.3200us  4.3200us  cudaGetDevice
                    0.00%  1.7080us         3     569ns     120ns  1.2680us  cuDeviceGetCount
                    0.00%     645ns         2     322ns     235ns     410ns  cuDeviceGet
                    0.00%     594ns         1     594ns     594ns     594ns  cuDeviceTotalMem
                    0.00%     549ns         1     549ns     549ns     549ns  cudaGetLastError
                    0.00%     449ns         1     449ns     449ns     449ns  cuModuleGetLoadingMode
                    0.00%     335ns         1     335ns     335ns     335ns  cuDeviceGetUuid

==23432== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
       9  1.3407MB  4.0000KB  2.0000MB  12.06641MB  1.062568ms  Host To Device
       8  1.5010MB  4.0000KB  2.0000MB  12.00781MB  967.4990us  Device To Host
      24         -         -         -           -  3.009018ms  Gpu page fault groups
Total CPU Page faults: 38
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

- CUDA GSL - Prefetch Execution (2048 x 2048):

```
Image loaded successfully!
Image dimensions: 2048x2048
Array size: 16777216
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 1.35444e-05
RMSE from image: 0.00368026
Validation from file
MSE: 2.09942e-06
RMSE from file 0.00144894
==23213== Profiling application: ./imageLoad
==23213== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  715.01ms        10  71.501ms  61.791ms  124.85ms  GaussianBlur(GaussianParams*)
      API calls:   86.06%  714.97ms         1  714.97ms  714.97ms  714.97ms  cudaDeviceSynchronize
                   12.16%  101.05ms         7  14.436ms  8.7370us  100.92ms  cudaMallocManaged
                    0.64%  5.3091ms         8  663.63us  7.1050us  1.4764ms  cudaMemPrefetchAsync
                    0.62%  5.1540ms         7  736.28us  135.00us  2.2917ms  cudaFree
                    0.50%  4.1673ms        10  416.73us  5.5630us  4.1098ms  cudaLaunchKernel
                    0.02%  139.88us       114  1.2260us     105ns  53.161us  cuDeviceGetAttribute
                    0.00%  13.198us         1  13.198us  13.198us  13.198us  cuDeviceGetName
                    0.00%  5.7770us         1  5.7770us  5.7770us  5.7770us  cuDeviceGetPCIBusId
                    0.00%  5.1130us         1  5.1130us  5.1130us  5.1130us  cudaGetDevice
                    0.00%  1.2930us         3     431ns     119ns     828ns  cuDeviceGetCount
                    0.00%  1.1290us         2     564ns     240ns     889ns  cuDeviceGet
                    0.00%     629ns         1     629ns     629ns     629ns  cuDeviceTotalMem
                    0.00%     422ns         1     422ns     422ns     422ns  cudaGetLastError
                    0.00%     394ns         1     394ns     394ns     394ns  cuModuleGetLoadingMode
                    0.00%     263ns         1     263ns     263ns     263ns  cuDeviceGetUuid

==23213== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
      27  1.7802MB  4.0000KB  2.0000MB  48.06641MB  4.193978ms  Host To Device
      26  1.8465MB  4.0000KB  2.0000MB  48.00781MB  3.852323ms  Device To Host
      96         -         -         -           -  7.435883ms  Gpu page fault groups
Total CPU Page faults: 146
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

CUDA GSL with Prefetch and Page Creation Execution

- CUDA GSL - Prefetch and Page Creation (512 x 512):

```
Image loaded successfully!
Image dimensions: 512x512
Array size: 1048576
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 2.3412e-05
RMSE from image: 0.00483859
Validation from file
MSE: 1.06483e-05
RMSE from file 0.00326317
==6459== Profiling application: ./imageLoad
==6459== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  76.603ms        10  7.6603ms  7.6464ms  7.6750ms  GaussianBlur(GaussianParams*)
      API calls:   62.22%  136.11ms         7  19.444ms  2.4650us  135.99ms  cudaMallocManaged
                   35.01%  76.580ms         1  76.580ms  76.580ms  76.580ms  cudaDeviceSynchronize
                    1.06%  2.3100ms        16  144.38us  3.3200us  1.0298ms  cudaMemPrefetchAsync
                    0.76%  1.6634ms         7  237.63us  15.645us  1.2151ms  cudaFree
                    0.45%  986.65us         1  986.65us  986.65us  986.65us  cuDeviceGetPCIBusId
                    0.41%  906.40us        10  90.639us  3.5980us  868.38us  cudaLaunchKernel
                    0.07%  158.53us       114  1.3900us     123ns  57.859us  cuDeviceGetAttribute
                    0.01%  19.533us         3  6.5110us     157ns  19.151us  cuDeviceGetCount
                    0.01%  13.124us         1  13.124us  13.124us  13.124us  cuDeviceTotalMem
                    0.01%  11.898us         1  11.898us  11.898us  11.898us  cuDeviceGetName
                    0.00%  6.2800us         1  6.2800us  6.2800us  6.2800us  cudaGetDevice
                    0.00%  1.3260us         2     663ns     168ns  1.1580us  cuDeviceGet
                    0.00%     585ns         1     585ns     585ns     585ns  cuModuleGetLoadingMode
                    0.00%     302ns         1     302ns     302ns     302ns  cudaGetLastError
                    0.00%     246ns         1     246ns     246ns     246ns  cuDeviceGetUuid

==6459== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
       5  616.00KB  4.0000KB  1.0000MB  3.007813MB  273.1130us  Host To Device
       5  616.00KB  4.0000KB  1.0000MB  3.007813MB  247.3850us  Device To Host
Total CPU Page faults: 16
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

- CUDA GSL - Prefetch and Page Creation (1024 x 1024):

```
Image loaded successfully!
Image dimensions: 1024x1024
Array size: 4194304
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 1.5554e-05
RMSE from image: 0.00394385
Validation from file
MSE: 4.27375e-06
RMSE from file 0.00206731
==6895== Profiling application: ./imageLoad
==6895== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  238.50ms        10  23.850ms  15.059ms  30.348ms  GaussianBlur(GaussianParams*)
      API calls:   67.57%  238.48ms         1  238.48ms  238.48ms  238.48ms  cudaDeviceSynchronize
                   31.13%  109.86ms         7  15.694ms  9.3190us  109.73ms  cudaMallocManaged
                    0.51%  1.8139ms        16  113.37us  3.1020us  461.07us  cudaMemPrefetchAsync
                    0.49%  1.7176ms        10  171.76us  3.4530us  1.6794ms  cudaLaunchKernel
                    0.25%  888.35us         7  126.91us  52.635us  220.61us  cudaFree
                    0.04%  153.69us       114  1.3480us     106ns  70.529us  cuDeviceGetAttribute
                    0.00%  13.189us         1  13.189us  13.189us  13.189us  cuDeviceGetName
                    0.00%  5.6820us         1  5.6820us  5.6820us  5.6820us  cuDeviceGetPCIBusId
                    0.00%  5.0290us         1  5.0290us  5.0290us  5.0290us  cudaGetDevice
                    0.00%  1.5840us         3     528ns     112ns  1.1710us  cuDeviceGetCount
                    0.00%     962ns         2     481ns     197ns     765ns  cuDeviceGet
                    0.00%     763ns         1     763ns     763ns     763ns  cuDeviceTotalMem
                    0.00%     599ns         1     599ns     599ns     599ns  cuModuleGetLoadingMode
                    0.00%     406ns         1     406ns     406ns     406ns  cudaGetLastError
                    0.00%     334ns         1     334ns     334ns     334ns  cuDeviceGetUuid

==6895== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
       8  1.5010MB  4.0000KB  2.0000MB  12.00781MB  1.058950ms  Host To Device
       8  1.5010MB  4.0000KB  2.0000MB  12.00781MB  965.3220us  Device To Host
Total CPU Page faults: 38
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

- CUDA GSL - Prefetch and Page Creation (2048 x 2048):

```
Image loaded successfully!
Image dimensions: 2048x2048
Array size: 16777216
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 1.35444e-05
RMSE from image: 0.00368026
Validation from file
MSE: 2.09942e-06
RMSE from file 0.00144894
==7234== Profiling application: ./imageLoad
==7234== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  702.13ms        10  70.213ms  60.632ms  121.42ms  GaussianBlur(GaussianParams*)
      API calls:   82.23%  702.01ms         1  702.01ms  702.01ms  702.01ms  cudaDeviceSynchronize
                   15.77%  134.65ms         7  19.236ms  11.059us  134.44ms  cudaMallocManaged
                    0.75%  6.4070ms        16  400.44us  3.9640us  1.7541ms  cudaMemPrefetchAsync
                    0.74%  6.2892ms        10  628.92us  5.2030us  6.1534ms  cudaLaunchKernel
                    0.49%  4.1806ms         7  597.23us  163.90us  1.9132ms  cudaFree
                    0.02%  178.65us       114  1.5670us     148ns  69.705us  cuDeviceGetAttribute
                    0.00%  15.329us         1  15.329us  15.329us  15.329us  cuDeviceGetName
                    0.00%  6.9400us         1  6.9400us  6.9400us  6.9400us  cuDeviceGetPCIBusId
                    0.00%  5.9070us         1  5.9070us  5.9070us  5.9070us  cudaGetDevice
                    0.00%  1.9920us         3     664ns     233ns  1.4850us  cuDeviceGetCount
                    0.00%     790ns         2     395ns     220ns     570ns  cuDeviceGet
                    0.00%     710ns         1     710ns     710ns     710ns  cuDeviceTotalMem
                    0.00%     489ns         1     489ns     489ns     489ns  cudaGetLastError
                    0.00%     446ns         1     446ns     446ns     446ns  cuModuleGetLoadingMode
                    0.00%     354ns         1     354ns     354ns     354ns  cuDeviceGetUuid

==7234== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
      28  1.7168MB  4.0000KB  2.0000MB  48.07031MB  4.193435ms  Host To Device
      27  1.7782MB  4.0000KB  2.0000MB  48.01172MB  3.854532ms  Device To Host
       1         -         -         -           -  81.43800us  Gpu page fault groups
Total CPU Page faults: 147
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

CUDA GSL with Prefetch, Page Creation, and Memory Advise Execution

- CUDA GSL - Prefetch, Page Creation, and MemAdvise (512 x 512):

```
Image loaded successfully!
Image dimensions: 512x512
Array size: 1048576
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 2.3412e-05
RMSE from image: 0.00483859
Validation from file
MSE: 1.06483e-05
RMSE from file 0.00326317
==8125== Profiling application: ./imageLoad
==8125== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  76.607ms        10  7.6607ms  7.6558ms  7.6680ms  GaussianBlur(GaussianParams*)
      API calls:   57.41%  107.74ms         7  15.392ms  2.4250us  107.62ms  cudaMallocManaged
                   40.81%  76.592ms         1  76.592ms  76.592ms  76.592ms  cudaDeviceSynchronize
                    0.70%  1.3136ms        16  82.098us  3.1080us  543.20us  cudaMemPrefetchAsync
                    0.45%  838.78us        10  83.878us  3.2930us  801.37us  cudaLaunchKernel
                    0.35%  649.88us         7  92.840us  14.455us  191.16us  cudaFree
                    0.17%  326.45us         8  40.806us  12.243us  70.910us  cudaMemAdvise
                    0.09%  169.98us       114  1.4910us     108ns  61.512us  cuDeviceGetAttribute
                    0.01%  14.119us         1  14.119us  14.119us  14.119us  cuDeviceGetName
                    0.00%  5.4720us         1  5.4720us  5.4720us  5.4720us  cuDeviceGetPCIBusId
                    0.00%  2.4500us         1  2.4500us  2.4500us  2.4500us  cudaGetDevice
                    0.00%  1.4860us         3     495ns     134ns  1.0810us  cuDeviceGetCount
                    0.00%     831ns         2     415ns     146ns     685ns  cuDeviceGet
                    0.00%     636ns         1     636ns     636ns     636ns  cuDeviceTotalMem
                    0.00%     538ns         1     538ns     538ns     538ns  cuModuleGetLoadingMode
                    0.00%     433ns         1     433ns     433ns     433ns  cudaGetLastError
                    0.00%     290ns         1     290ns     290ns     290ns  cuDeviceGetUuid

==8125== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
       4  769.00KB  4.0000KB  1.0000MB  3.003906MB  272.0260us  Host To Device
       3  1.0000MB  1.0000MB  1.0000MB  3.000000MB  243.8020us  Device To Host
Total CPU Page faults: 15
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

- CUDA GSL - Prefetch, Page Creation, and MemAdvise (1024 x 1024):

```
Image loaded successfully!
Image dimensions: 1024x1024
Array size: 4194304
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 1.5554e-05
RMSE from image: 0.00394385
Validation from file
MSE: 4.27375e-06
RMSE from file 0.00206731
==8602== Profiling application: ./imageLoad
==8602== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  235.24ms        10  23.524ms  15.063ms  30.329ms  GaussianBlur(GaussianParams*)
      API calls:   62.48%  235.20ms         1  235.20ms  235.20ms  235.20ms  cudaDeviceSynchronize
                   35.68%  134.31ms         7  19.187ms  13.120us  134.14ms  cudaMallocManaged
                    0.63%  2.3732ms        16  148.32us  3.9750us  560.14us  cudaMemPrefetchAsync
                    0.42%  1.5952ms         7  227.89us  170.87us  340.79us  cudaFree
                    0.38%  1.4451ms         8  180.63us  17.576us  406.77us  cudaMemAdvise
                    0.36%  1.3364ms        10  133.64us  5.4740us  1.2773ms  cudaLaunchKernel
                    0.04%  147.18us       114  1.2910us     106ns  57.741us  cuDeviceGetAttribute
                    0.00%  14.517us         1  14.517us  14.517us  14.517us  cuDeviceGetName
                    0.00%  7.5870us         1  7.5870us  7.5870us  7.5870us  cuDeviceGetPCIBusId
                    0.00%  6.2540us         1  6.2540us  6.2540us  6.2540us  cudaGetDevice
                    0.00%  1.3380us         3     446ns     134ns     935ns  cuDeviceGetCount
                    0.00%  1.1060us         2     553ns     230ns     876ns  cuDeviceGet
                    0.00%     575ns         1     575ns     575ns     575ns  cuModuleGetLoadingMode
                    0.00%     545ns         1     545ns     545ns     545ns  cudaGetLastError
                    0.00%     416ns         1     416ns     416ns     416ns  cuDeviceTotalMem
                    0.00%     299ns         1     299ns     299ns     299ns  cuDeviceGetUuid

==8602== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
       7  1.7148MB  4.0000KB  2.0000MB  12.00391MB  1.049413ms  Host To Device
       6  2.0000MB  2.0000MB  2.0000MB  12.00000MB  962.2810us  Device To Host
Total CPU Page faults: 37
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

- CUDA GSL - Prefetch, Page Creation, and MemAdvise (2048 x 2048):

```
Image loaded successfully!
Image dimensions: 2048x2048
Array size: 16777216
Will Process Image
Done Process Image
Image Saved
Validation from image
MSE: 1.35444e-05
RMSE from image: 0.00368026
Validation from file
MSE: 2.09942e-06
RMSE from file 0.00144894
==8991== Profiling application: ./imageLoad
==8991== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:  100.00%  716.32ms        10  71.632ms  60.948ms  121.34ms  GaussianBlur(GaussianParams*)
      API calls:   84.10%  716.30ms         1  716.30ms  716.30ms  716.30ms  cudaDeviceSynchronize
                   13.86%  118.09ms         7  16.870ms  9.0630us  117.92ms  cudaMallocManaged
                    0.57%  4.8603ms        10  486.03us  3.5270us  4.8212ms  cudaLaunchKernel
                    0.57%  4.8527ms        16  303.29us  3.3760us  1.4720ms  cudaMemPrefetchAsync
                    0.45%  3.8386ms         7  548.37us  385.62us  719.72us  cudaFree
                    0.43%  3.6225ms         8  452.81us  20.662us  1.0548ms  cudaMemAdvise
                    0.02%  143.38us       114  1.2570us     107ns  56.443us  cuDeviceGetAttribute
                    0.00%  12.808us         1  12.808us  12.808us  12.808us  cuDeviceGetName
                    0.00%  7.2780us         1  7.2780us  7.2780us  7.2780us  cudaGetDevice
                    0.00%  5.5140us         1  5.5140us  5.5140us  5.5140us  cuDeviceGetPCIBusId
                    0.00%  1.3390us         3     446ns     146ns     881ns  cuDeviceGetCount
                    0.00%     821ns         2     410ns     186ns     635ns  cuDeviceGet
                    0.00%     671ns         1     671ns     671ns     671ns  cuDeviceTotalMem
                    0.00%     458ns         1     458ns     458ns     458ns  cudaGetLastError
                    0.00%     332ns         1     332ns     332ns     332ns  cuModuleGetLoadingMode
                    0.00%     279ns         1     279ns     279ns     279ns  cuDeviceGetUuid

==8991== Unified Memory profiling result:
Device "Tesla T4 (0)"
   Count  Avg Size  Min Size  Max Size  Total Size  Total Time  Name
      25  1.9202MB  4.0000KB  2.0000MB  48.00391MB  4.182204ms  Host To Device
      24  2.0000MB  2.0000MB  2.0000MB  48.00000MB  3.848360ms  Device To Host
Total CPU Page faults: 145
```

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

Execution Time Comparisons

- Sequential vs Parallel (512x512 px)

	Sequential	Parallel				Speed Up
	C++	GSL	GSL + Prefetch	GSL + Prefetch + Page Creation	GSL + Prefetch + Page Creation + Mem Advise	C++ vs Mem Advise Kernel
Average run time (10 calls)	11,955.1 ms	7.7283ms	7.6563ms	7.6603ms	7.6607ms	
Host to Device		0.4424540ms	0.3583930ms	0.273113ms	0.272026ms	
Device to Host		0.3033850ms	0.2440280ms	0.247385ms	0.243802ms	
GPU Kernel Time		8.474139ms	8.258721ms	8.180798ms	8.176528ms	1,462.12

- Sequential vs Parallel (1024x1024 px)

	Sequential	Parallel				Speed Up
	C++	GSL	GSL + Prefetch	GSL + Prefetch + Page Creation	GSL + Prefetch + Page Creation + Mem Advise	C++ vs Mem Advise Kernel
Average run time (10 calls)	50,536.7ms	22.636ms	24.260ms	23.850ms	23.524ms	
Host to Device		1.235905ms	1.060581ms	1.05895ms	1.049413ms	
Device to Host		1.104040ms	0.9667900ms	0.965322ms	0.962281ms	
GPU Kernel Time		24.975945ms	26.287371ms	25.874272ms	25.535694ms	1,979.06

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

- Sequential vs Parallel (2048x2048 px)

	Sequential	Parallel				Speed Up
	C++	GSL	GSL + Prefetch	GSL + Prefetch + Page Creation	GSL + Prefetch + Page Creation + Mem Advise	C++ vs Mem Advise Kernel
Average run time (10 calls)	202,619 ms	73.874ms	73.701ms	70.213ms	71.632ms	
Host to Device		4.983810ms	4.192919ms	4.193435ms	4.182204ms	
Device to Host		4.291367ms	3.856018ms	3.854532ms	3.848360ms	
GPU Kernel Time		83.149177ms	81.749937ms	78.260967ms	79.653564ms	2,543.75

Notes:

- C++ Sequential vs CUDA Parallel has a very large gap between their execution time.
  - CUDA really works well with images, especially for Gaussian Blur
  - C++ Sequential seems to have a very large disadvantage compared to CUDA's parallelism.
  - A comparison between a parallel version of the C++ implementation would've been a nice comparison against cuda.
- We can clearly see the total GPU Kernel Time reduction for every optimization step we add to the base GSL Kernel.
  - Although for Memory Advise, the 2048x2048 resolution seem to slow down very so slightly against the previous kernel (i.e. Page Creation).

CSC612M - G01 - MP2

Members:
Abello, Hans Bautista, Lorenzo Cala, John Raymond Tibule, Geena

Validation Comparison

- **From Image vs Image**

		GSL	GSL + Prefetch	GSL + Prefetch + Page Creation	GSL + Prefetch + Page Creation + Mem Advise
512x512	MSE	2.3412e-05	2.3412e-05	2.3412e-05	2.3412e-05
	RMSE	0.00483859	0.00483859	0.00483859	0.00483859
1024x1024	MSE	1.5554e-05	1.5554e-05	1.5554e-05	1.5554e-05
	RMSE	0.00394385	0.00394385	0.00394385	0.00394385
2048x2048	MSE	1.35444e-05	1.35444e-05	1.35444e-05	1.35444e-05
	RMSE	0.00368026	0.00368026	0.00368026	0.00368026

Notes:

- The MSE between C++ and CUDA results did not meet the requirement of being less than $1e^{-6}$. One of the factors for this result is that when downloading or saving the output image, the RGB channels are converted from float to integer. This conversion causes truncation of the original floating-point values, and these truncated values are then used during comparison.

- **From CUDA computed RGB Channel vs C++ computed RGB Channel**

		GSL	GSL + Prefetch	GSL + Prefetch + Page Creation	GSL + Prefetch + Page Creation + Mem Advise
512x512	MSE	1.06483e-05	1.06483e-05	1.06483e-05	1.06483e-05
	RMSE	0.00326317	0.00326317	0.00326317	0.00326317
1024x1024	MSE	4.27375e-06	4.27375e-06	4.27375e-06	4.27375e-06
	RMSE	0.00206731	0.00206731	0.00206731	0.00206731

CSC612M - G01 - MP2

Members:

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2048x2048	MSE	2.09942e-06	2.09942e-06	2.09942e-06	2.09942e-06
	RMSE	0.00144894	0.00144894	0.00144894	0.00144894

Notes:

- We implemented this by saving the RGB channel values into a CSV file from the C++ Kernel runs.
- We got a lower MSE and RMSE compared to the image vs image validation.
- Still we weren't able to achieve the $<1e^{-06}$ range.