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ECE 408/CS483 Milestone 3 Report

0. List Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images from your basic forward convolution kernel in milestone 2. This will act as your baseline this milestone.

Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.1762*	*0.6354*	*0.8116*	*0.86*
1000	*1.6275*	*6.2637*	*7.8912*	*0.886*
10000	*16.0021*	*62.2321*	*78.2342*	*0.8714*

1. **Optimization 1:** Weight matrix (kernel values) in constant memory

    a. Which optimization did you choose to implement and why did you choose that optimization technique.

    Use cudaMemcpyToSymbol to copy kernel to constant memory. It is very easy to implement, and the improvement is significant.

    b. How does the optimization work? Did you think the optimization would increase performance of the forward convolution? Why? Does the optimization synergize with any of your previous optimizations?

    - Use cudaMemcpyToSymbol to copy kernel to constant memory in conv_forward_gpu_prolog.
      ```
      cudaMemcpyToSymbol(Kernel, host_k, kSize, 0, cudaMemcpyHostToDevice);
      ```
    - The optimization would increase performance, because constant memory access is much faster than global memory access.
    - The optimization synergize with all other optimizations.

c. List the Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images using this optimization (including any previous optimizations also used).

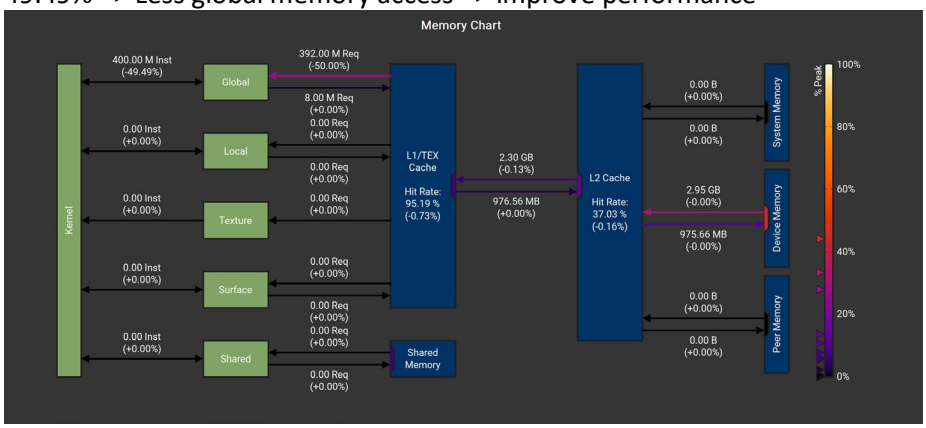
Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.1597*	*0.5726*	*0.7323*	*0.86*
1000	*1.4825*	*5.6488*	*7.1313*	*0.886*
10000	*14.5445*	*57.1707*	*71.7152*	*0.8714*

d. Was implementing this optimization successful in improving performance? Why or why not? Include profiling results from *nsys* and *Nsight-Compute* to justify your answer, directly comparing to your baseline (or the previous optimization this one is built off of).

- The Total Execution Time decrease to 92% of baseline (8% faster) after the optimization. (Use batch size = 10000 to compare)
- This optimization successful in improving performance.
- From nsys: With this optimization, conv_forward_kernel total time decrease.

	baseline	This optimization
conv_forward_kernel	79482366	72374484

- From Memory Chart we can see that data transfer between kernel and Global - 49.49% => Less global memory access => improve performance



e. What references did you use when implementing this technique?

Mp4: 3D Convolution

2. **Optimization 2:** Tuning with restrict and loop unrolling

   a. Which optimization did you choose to implement and why did you choose that optimization technique.

      I choose Tuning with restrict and loop unrolling because it is also easy to implement. And loop unrolling can avoiding some Branch Divergence, which will improve performance.

   b. How does the optimization work? Did you think the optimization would increase performance of the forward convolution? Why? Does the optimization synergize with any of your previous optimizations?

      - Add __restrict__ prefix to all pointers declartion.
      - Unroll convolution calculation

Before Unroll	`for (int p = 0; p < K; p++) {`
	`  for (int q = 0; q < K; q++) {`
	`  acc += x4d(b, c, h + p, w + q) * k4d_constant(m, c, p, q);`
	`  }`
	`}`

After Unroll	`acc += x4d(b, c, h + 0, w + 0) * k4d_constant(m, c, 0, 0) +`
	`  x4d(b, c, h + 0, w + 1) * k4d_constant(m, c, 0, 1) +`
	`  x4d(b, c, h + 0, w + 2) * k4d_constant(m, c, 0, 2) +`
	`  x4d(b, c, h + 0, w + 3) * k4d_constant(m, c, 0, 3) +`
	`  x4d(b, c, h + 0, w + 4) * k4d_constant(m, c, 0, 4) +`
	`  x4d(b, c, h + 0, w + 5) * k4d_constant(m, c, 0, 5) +`
	`  x4d(b, c, h + 0, w + 6) * k4d_constant(m, c, 0, 6) +`
	`  x4d(b, c, h + 1, w + 0) * k4d_constant(m, c, 1, 0) +`
	`  x4d(b, c, h + 1, w + 1) * k4d_constant(m, c, 1, 1) +`
	`  x4d(b, c, h + 1, w + 2) * k4d_constant(m, c, 1, 2) +`
	`  x4d(b, c, h + 1, w + 3) * k4d_constant(m, c, 1, 3) +`
	`  x4d(b, c, h + 1, w + 4) * k4d_constant(m, c, 1, 4) +`
	`  x4d(b, c, h + 1, w + 5) * k4d_constant(m, c, 1, 5) +`
	`  x4d(b, c, h + 1, w + 6) * k4d_constant(m, c, 1, 6) +`
	. . .

      - I think the optimization would increase performance of the forward convolution, because loop unrolling can avoiding some Branch Divergence, which will improve performance.
      - The optimization synergize with all other optimizations. In the above screenshot you can see that I use k4d_constant to calculate convolution.

   c. List the Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images using this optimization (including any previous optimizations also used).

Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.1563*	*0.4187*	*0.575*	*0.86*
1000	*1.2345*	*3.9597*	*5.1942*	*0.886*
10000	*11.5244*	*40.5754*	*52.0998*	*0.8714*

d. Was implementing this optimization successful in improving performance? Why or why not? Include profiling results from *nsys* and *Nsight-Compute* to justify your answer, directly comparing to your baseline (or the previous optimization this one is built off of).

- The Total Execution Time decrease to 73% of previous optimization (37% faster) after the optimization. (Use batch size = 10000 to compare)
- This optimization successful in improving performance.
- From nsys: With this optimization, conv_forward_kernel total time decrease.

	Previous code	This optimization
conv_forward_kernel	72374484	52457030

e. What references did you use when implementing this technique?

- *https://www.nvidia.com/docs/IO/116711/sc11-unrolling-parallel-loops.pdf*
- *https://developer.nvidia.com/blog/cuda-pro-tip-optimize-pointer-aliasing/*

Optimization 3: Using Streams to overlap computation with data transfer

a. Which optimization did you choose to implement and why did you choose that optimization technique.

I choose to implement using Streams to overlap computation with data transfer because it is not hard to implement, also it only influence dimension x of block (Batch size), so I only have to modify one line in kernel.

b. How does the optimization work? Did you think the optimization would increase performance of the forward convolution? Why? Does the optimization synergize with any of your previous optimizations?

- Create cuda stream and use cudaMemcpyAsync to copy data to device asynchronously in conv_forward_gpu_prolog()

```
const int xStreamSize = B * C * H * W / STREAM_NUM;
const int xStreamByte = xStreamSize * sizeof(float);
const int yStreamSize = B * M * H_out * W_out / STREAM_NUM;
const int yStreamByte = yStreamSize * sizeof(float);
for (int i = 0; i < STREAM_NUM; i++) {
    cudaStreamCreate(&stream[i]);
}
for (int i = 0; i < STREAM_NUM; i++) {
    int offset = i * xStreamSize;
    cudaMemcpyAsync((void *)&(*device_x_ptr)[offset], (void *)&(host_x[offset]), xStreamByte,
                    cudaMemcpyHostToDevice, stream[i]);
}
```

- In kernel I only have to modify one line.

```
int b = blockIdx.x + offset;
```

- Defined streamSize than call conv_forwanr_kernel with stream[i] asynchronously

```
const int streamSize = B / STREAM_NUM;
dim3 DimGrid(streamSize, M, H_grid * W_grid);
dim3 DimBlock(TILE_WIDTH, TILE_WIDTH, 1);
for (int i = 0; i < STREAM_NUM; i++) {
    int offset = i * streamSize;
    conv_forward_kernel<<<DimGrid, DimBlock, 0, stream[i]>>>(device_y, device_x, B, M, C, H, W,
                                                             K, offset);
}
```

- Copy data back to host asynchronously in conv_forward_gpu_epilog()

```
for (int i = 0; i < STREAM_NUM; i++) {
    int offset = i * yStreamSize;
    cudaMemcpyAsync(&host_y[offset], &device_y[offset], yStreamByte, cudaMemcpyDeviceToHost,
                    stream[i]);
}
```

- I think the optimization would increase performance of the forward convolution, because using Streams can overlap computation with data transfer, so that some kernel can start calculating the segment of data that already copied to device while other segments of data are still copying, which will improve performance.
- The optimization synergize with all other optimizations. Because all I have to do is modify “int b = blockIdx.x + offset;” in kernel, change cudaMemcpy to cudaMemcpyAsync, and use cudaCreateStream to create Streams.

c. List the Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images using this optimization (including any previous optimizations also used).

Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.5393*	*0.6613*	*1.2006*	*0.86*
1000	*1.0830*	*4.9036*	*5.9866*	*0.886*
10000	*10.1244*	*38.2340*	*48.3584*	*0.8714*

d. Was implementing this optimization successful in improving performance? Why or why not? Include profiling results from *nsys* and *Nsight-Compute* to justify your answer, directly comparing to your baseline (or the previous optimization this one is built off of).

- The Total Execution Time decrease to 93% of previous optimization (7.5% faster) after the optimization. (Use batch size = 10000 to compare)
- This optimization successful in improving performance.
- From nsys: With this optimization, conv_forward_kernel total time decrease.

	Previous code	This optimization
conv_forward_kernel	52457030	52004476

e. What references did you use when implementing this technique?

- https://developer.nvidia.com/blog/how-overlap-data-transfers-cuda-cc/
- ece408-lecture22-GPU-Data-Transfer-sjp-FL21.pdf

3. **Optimization 4:** Multiple kernel implementations for different layer sizes
(Delete this section blank if you did not implement this many optimizations.)

a. Which optimization did you choose to implement and why did you choose that optimization technique.

I choose to implement multiple kernel implementations for different layer sizes because I want to tune kernel code of different layer separately to optimize performance.

b. How does the optimization work? Did you think the optimization would increase performance of the forward convolution? Why? Does the optimization synergize with any of your previous optimizations?

- I use C to identify which layer is using the code, C == 1 means layer and C == 4 means layer2.
- I copy the previous kernel to “conv_forward_kernel_C1” and “conv_forward_kernel_C4”.
- For conv_forward_kernel_C1, when doing convolution, c is not iterated because c is always 0.
- For conv_forward_kernel_C4, when doing convolution, C is set to 4, c is iterated 4 times, and I use “#pragma unroll 4” to unroll the for loop.
- I think the optimization would increase performance of the forward convolution, because conv_forward_kernel_C1 doesn’t have to iterate through c, and the iterate of c in conv_forward_kernel_C4 is unrolled.
- The optimization synergize with all other optimizations. Because both conv_forward_kernel_C1 and conv_forward_kernel_C4 are copied from conv_forward_kernel, which has all the optimization I have done before.

c. List the Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images using this optimization (including any previous optimizations also used).

Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.2336*	*0.7981*	*1.0317*	*0.86*
1000	*1.0609*	*6.0966*	*7.1575*	*0.886*
10000	*10.1129*	*38.1551*	*48.2680*	*0.8714*

d. Was implementing this optimization successful in improving performance? Why or why not? Include profiling results from *nsys* and *Nsight-Compute* to justify your answer, directly comparing to your baseline (or the previous optimization this one is built off of).

- The Total Execution Time decrease to 99.8% of previous optimization (0.2% faster) after the optimization. (Use batch size = 10000 to compare)
- This optimization successful in improving performance.
- From nsys: With this optimization, conv_forward_kernel total time decrease.

	Previous code	This optimization
conv_forward_kernel	52457030	Sum: 52067454
conv_forward_kernel_C1	-	11029638
conv_forward_kernel_C4	-	41037816

e. What references did you use when implementing this technique?

- Readme of the project.
- https://forums.developer.nvidia.com/t/pragma-unroll/3042

4. **Optimization 5:** Sweeping various parameters to find best values
(Delete this section if you did not implement this many optimizations.)

a. Which optimization did you choose to implement and why did you choose that optimization technique.

I choose Sweeping various parameters to find best values because it is easy to implement, just change the constants and try to find the parameters that produce the best performance.

b. How does the optimization work? Did you think the optimization would increase performance of the forward convolution? Why? Does the optimization synergize with any of your previous optimizations?

- I modify Layer 1 tile size, Layer 2 tile size, Stream Num, and Row/Col major access pattern, to get the best parameters.
- *I think the* optimization will help me find a parameters set that has better performance than before, or maybe the parameters set I used before already has the best performance.
- The optimization synergize with all other optimizations. Because all I have to do is modify Layer 1 tile size, Layer 2 tile size, Stream Num. I have already implemented all of them before.

c. List the Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images using this optimization (including any previous optimizations also used).

Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.1335*	*0.7207*	*0.8542*	*0.86*
1000	*1.0468*	*5.7384*	*6.7852*	*0.886*
10000	*10.1221*	*36.8542*	*46.9763*	*0.8714*

d. Was implementing this optimization successful in improving performance? Why or why not? Include profiling results from *nsys* and *Nsight-Compute* to justify your answer, directly comparing to your baseline (or the previous optimization this one is built off of).

- The Total Execution Time decrease to 97% of previous optimization (3% faster) after the optimization. (Use batch size = 10000 to compare)
- This optimization successful in improving performance.
- *In previous optimizations I set StreamNum = 100, but in this optimization I find out that StreamNum = 50 has better performance.*
- Below is result of my sweeping. Batch size = 10000

Stream Num = 100

Layer 1 Tile Size	*Layer 2 Tile Size*	Op Time 1	Op Time 2	Total Op Time
8	*8*	*13.5250*	*108.5370*	*122.0620*
16	*16*	*10.1129*	*38.1551*	*48.2680*
32	*32*	*12.2763*	*57.1044*	*69.3807*
16	*32*	*10.2053*	*56.7387*	*66.9440*
32	*16*	*12.2754*	*38.3403*	*50.6157*

Layer 1 Tile Size = 16

Layer 2 Tile Size = 16

Stream Num	Op Time 1	Op Time 2	Total Op Time
5	*10.4447*	*39.7660*	*50.2107*
10	*12.1201*	*39.3244*	*51.4445*
20	*10.2465*	*37.6816*	*47.9281*
25	*10.2102*	*37.5382*	*47.7484*
50	*10.1221*	*36.8542*	*46.9763*
100	*10.1129*	*38.1551*	*48.2680*

Stream Num = 50
Layer 1 Tile Size = 16
Layer 2 Tile Size = 16

Row major access	*10.1221*	*36.8542*	*46.9763*
Col major access	*10.1824*	*40.5148*	*50.6972*

- From nsys: With this optimization, conv_forward_kernel_C1 + conv_forward_kernel_C4 total time decrease.

	Previous code	This optimization
conv_forward_kernel Sum	52067454	49032230
conv_forward_kernel_C1	11029638	10572540
conv_forward_kernel_C4	41037816	38459690

e. What references did you use when implementing this technique?

- Readme of the project.

5. **Optimization 6:** Tiled shared memory convolution
(Delete this section if you did not implement this many optimizations.)

a. Which optimization did you choose to implement and why did you choose that optimization technique.

I choose Tiled shared memory convolution because we already implement it in mp4, and tiled shared memory is supposed to be faster than using global memory.

b. How does the optimization work? Did you think the optimization would increase performance of the forward convolution? Why? Does the optimization synergize with any of your previous optimizations?

- I implement strategy two, block size covers input tile.
- Shared memory is much faster than global memory, so if we want to access a data multiple times, saving the data to shared memory will improve performance.
- The optimization is supposed to synergize with all other optimizations. But after testing the optimization, I find out that it actually make my code slower, so I didn't merge it into my code.

c. List the Op Times, whole program execution time, and accuracy for batch size of 100, 1k, and 10k images using this optimization (including any previous optimizations also used).

Batch Size	Op Time 1	Op Time 2	Total Execution Time	Accuracy
100	*0.3287*	*1.0055*	*1.3342*	*0.86*
1000	*3.1591*	*9.9128*	*13.0719*	*0.886*
10000	*31.2918*	*99.4144*	*130.7062*	*0.8714*

d. Was implementing this optimization successful in improving performance? Why or why not? Include profiling results from *nsys* and *Nsight-Compute* to justify your answer, directly comparing to your baseline (or the previous optimization this one is built off of).

- The Total Execution Time increase to 167% of baseline (60% slower) after the optimization. (Use batch size = 10000 to compare)
- *The optimization failed in improving performance.*
- From nsys: With this optimization, conv_forward_kernel total time increase.

	baseline	This optimization
conv_forward_kernel	79482366	131470546

e. What references did you use when implementing this technique?

Mp4: 3D Convolution