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ECE 408 Final Project Report
MILESTONE 1

DELIVERABLES:

1. List of all kernels that collectively consume more than 90% of program time
    a. CUDA memcpy HtoD (39.39%)
    b. void cudnn::detail::implicit_convolve_sgemm (20.65%)
    c. Volta_cgemm_64x32_tn (12.11%)
    d. Op_generic_tensor_kernel (7.15%)
    e. Fft2d_c2r_32x32 (5.74%)
    f. Volta_sgemm_128x128_tn (5.72%)
2. List of CUDA API that consume more than 90% of program time
    a. cudaStreamCreateWithFlags (42.32%)
    b. cudaMemGetInfo (33.58%)
    c. cudaFree (21.37%)
3. Explanation of difference between kernels and API calls
    a. CUDA kernels are essentially C functions defined by the user that are executed by threads on the GPU. CUDA API calls extend functionality through the runtime and Driver APIs which also hold the context. The context holds all of the management data to control and use the device (allocated memory, loaded modules that contain device code, mapping between CPU and GPU memory, etc). (https://stackoverflow.com/questions/43244645/what-is-a-cuda-context)
4. Output of RAI running on MXNet on the CPU (time m1.1.py)

```
EvalMetric: {'accuracy': 0.8236}
8.83user 3.76system 0:05.01elapsed 251%CPU (0avgtext+0avgdata
2470596maxresident)k
0inputs+2824outputs (0major+667706minor)pagefaults 0swaps
```

5. List Program Run time
    a. 5.01 seconds
6. Output of RAI running on MXNet on the GPU

```
EvalMetric: {'accuracy': 0.8236}
4.28user 3.32system 0:04.32elapsed 176%CPU (0avgtext+0avgdata
2843476maxresident)k
8inputs+4552outputs (0major+660709minor)pagefaults 0swaps
```

7. List Program Run time
    a. 4.32 seconds

Example NVPROF output

```
==383== NVPROF is profiling process 383, command: python m1.2.py
Loading model... done
New Inference
EvalMetric: {'accuracy': 0.8236}
==383== Profiling application: python m1.2.py
==383== Profiling result:
         Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   39.39%  16.127ms        20  806.35us  1.0880us  15.480ms  [CUDA memcpy
HtoD]
              20.65%  8.4531ms         1  8.4531ms  8.4531ms  8.4531ms  void
cudnn::detail::implicit_convolve_sgemm<float, float, int=1024, int=5, int=5, int=3, int=3, int=3,
int=1, bool=1, bool=0, bool=1>(int, int, int, float const *, int, float*,
cudnn::detail::implicit_convolve_sgemm<float, float, int=1024, int=5, int=5, int=3, int=3, int=3,
int=1, bool=1, bool=0, bool=1>*, kernel_conv_params, int, float, float, int, float, float, int, int)
              12.11%  4.9587ms         1  4.9587ms  4.9587ms  4.9587ms
volta_cgemm_64x32_tn
               7.15%  2.9281ms         2  1.4641ms  24.864us  2.9033ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
               5.74%  2.3506ms         1  2.3506ms  2.3506ms  2.3506ms  void
fft2d_c2r_32x32<float, bool=0, bool=0, unsigned int=1, bool=0, bool=0>(float*, float2 const *, int,
int, int, int, int, int, int, int, int, float, float, cudnn::reduced_divisor, bool, float*, float*, int2, int, int)
               5.72%  2.3400ms         1  2.3400ms  2.3400ms  2.3400ms
volta_sgemm_128x128_tn
               4.60%  1.8821ms         1  1.8821ms  1.8821ms  1.8821ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
               3.80%  1.5541ms         1  1.5541ms  1.5541ms  1.5541ms  void
fft2d_r2c_32x32<float, bool=0, unsigned int=0, bool=0>(float2*, float const *, int, int, int, int, int,
int, int, int, int, cudnn::reduced_divisor, bool, int2, int, int)
               0.37%  152.42us         1  152.42us  152.42us  152.42us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
               0.18%  75.072us         1  75.072us  75.072us  75.072us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                0.07%  30.144us        13  2.3180us  1.2160us  7.5200us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                0.06%  25.440us         1  25.440us  25.440us  25.440us  volta_sgemm_32x128_tn
                0.06%  23.776us         2  11.888us  2.5920us  21.184us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
                0.04%  15.968us         1  15.968us  15.968us  15.968us  void
fft2d_r2c_32x32<float, bool=0, unsigned int=1, bool=0>(float2*, float const *, int, int, int, int, int,
int, int, int, int, cudnn::reduced_divisor, bool, int2, int, int)
                0.02%  10.016us         9  1.1120us     992ns  1.5360us  [CUDA memset]
0.02%  7.3280us         1  7.3280us  7.3280us  7.3280us  [CUDA memcpy DtoH]
                0.01%  4.8000us         1  4.8000us  4.8000us  4.8000us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
                0.01%  3.2640us         1  3.2640us  3.2640us  3.2640us  void flip_filter<float,
float>(float*, float const *, int, int, int, int)
                0.01%  2.6550us         1  2.6550us  2.6550us  2.6550us
compute_gemm_pointers(float2**, float2 const *, int, float2 const *, int, float2 const *, int, int)
     API calls:   42.32%  3.00705s        22  136.68ms  12.851us  1.56016s
cudaStreamCreateWithFlags
               33.58%  2.38633s        24  99.430ms  104.11us  2.38104s  cudaMemGetInfo
               21.37%  1.51843s        19  79.917ms     834ns  408.31ms  cudaFree
                1.41%  99.952ms       912  109.60us     308ns  53.410ms  cudaFuncSetAttribute
                0.46%  32.478ms         9  3.6086ms  33.713us  15.513ms  cudaMemcpy2DAsync
                0.31%  21.688ms        29  747.87us  3.4170us  9.9361ms  cudaStreamSynchronize
                0.18%  12.549ms        68  184.55us  5.7180us  2.8536ms  cudaMalloc
                0.12%  8.4657ms       216  39.192us     889ns  5.9292ms
cudaEventCreateWithFlags
                0.10%  7.2073ms         6  1.2012ms  1.1090us  7.1385ms  cudaEventCreate
                0.07%  4.7327ms         4  1.1832ms  424.50us  1.7514ms
cudaGetDeviceProperties
```

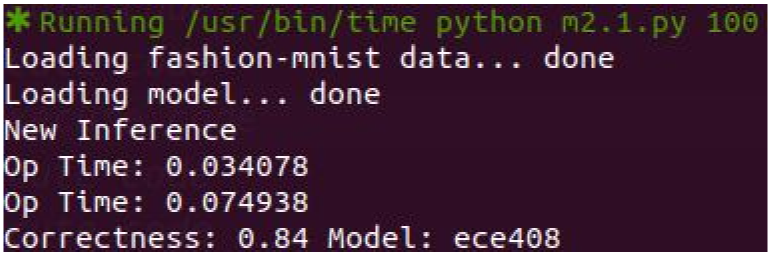
```
        0.03%  2.4824ms       375  6.6190us     284ns  331.03us  cuDeviceGetAttribute
        0.01%  789.41us         2  394.70us  51.193us  738.21us  cudaHostAlloc
        0.01%  621.86us        30  20.728us  7.9970us  81.572us  cudaLaunchKernel
        0.01%  610.11us         4  152.53us  94.017us  275.55us  cuDeviceTotalMem
        0.01%  599.74us         4  149.94us  77.489us  246.88us  cudaStreamCreate
        0.01%  469.55us        12  39.128us  5.9160us  88.270us  cudaMemcpy
        0.01%  389.25us         9  43.250us  9.3750us  212.87us  cudaMemsetAsync
        0.00%  323.78us       210  1.5410us     566ns  16.920us  cudaDeviceGetAttribute
        0.00%  289.34us         4  72.334us  43.955us  103.40us  cuDeviceGetName
        0.00%  172.31us         8  21.538us  13.755us  44.913us
cudaStreamCreateWithPriority
        0.00%  155.99us        32  4.8740us  1.4400us  15.018us  cudaSetDevice
        0.00%  106.65us       564     189ns      75ns     611ns  cudaGetLastError
        0.00%  43.911us        18  2.4390us     599ns  4.7600us  cudaGetDevice
        0.00%  23.685us         6  3.9470us  1.6840us  7.0150us  cudaEventRecord
        0.00%  13.089us         1  13.089us  13.089us  13.089us  cudaBindTexture
        0.00%  9.2010us         3  3.0670us  1.8970us  4.3720us  cudaStreamWaitEvent
        0.00%  7.9230us         1  7.9230us  7.9230us  7.9230us  cuDeviceGetPCIBusId
        0.00%  7.0690us         2  3.5340us  2.3280us  4.7410us
cudaHostGetDevicePointer
        0.00%  6.1030us         6  1.0170us     401ns  2.3180us  cuDeviceGetCount
        0.00%  6.0000us         2  3.0000us  1.5100us  4.4900us
cudaDeviceGetStreamPriorityRange
        0.00%  5.2940us        18     294ns     121ns     673ns  cudaPeekAtLastError
        0.00%  4.7520us         5     950ns     474ns  1.7100us  cuDeviceGet
        0.00%  4.1730us         3  1.3910us     809ns  2.2560us  cuInit
        0.00%  3.8930us         1  3.8930us  3.8930us  3
.8930us  cudaEventQuery
        0.00%  3.3850us         1  3.3850us  3.3850us  3.3850us  cudaUnbindTexture
        0.00%  2.4530us         4     613ns     354ns  1.2000us  cuDeviceGetUuid
        0.00%  1.9340us         3     644ns     330ns  1.1950us  cuDriverGetVersion
        0.00%  1.7790us         4     444ns     262ns     777ns  cudaGetDeviceCount
```

MILESTONE 2

DELIVERABLES:

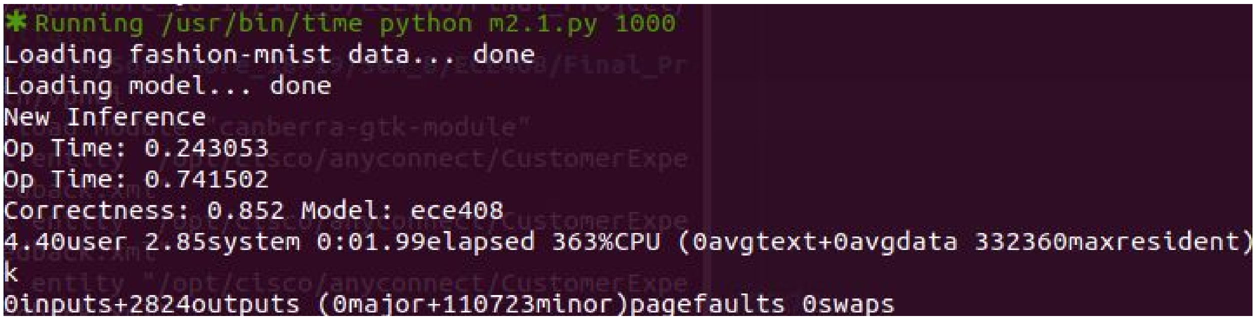
- List whole program run times
- List Op. times

Run #1: 100



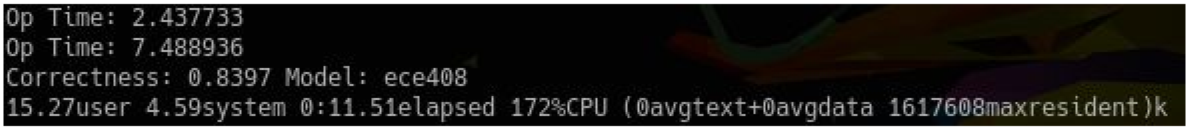
```
* Running /usr/bin/time python m2.1.py 100
Loading fashion-mnist data... done
Loading model... done
New Inference
Op Time: 0.034078
Op Time: 0.074938
Correctness: 0.84 Model: ece408
```

Run #2: 1,000



```
* Running /usr/bin/time python m2.1.py 1000
Loading fashion-mnist data... done
Loading model... done
New Inference
Op Time: 0.243053
Op Time: 0.741502
Correctness: 0.852 Model: ece408
4.40user 2.85system 0:01.99elapsed 363%CPU (0avgtext+0avgdata 332360maxresident)
k
0inputs+2824outputs (0major+110723minor)pagefaults 0swaps
```

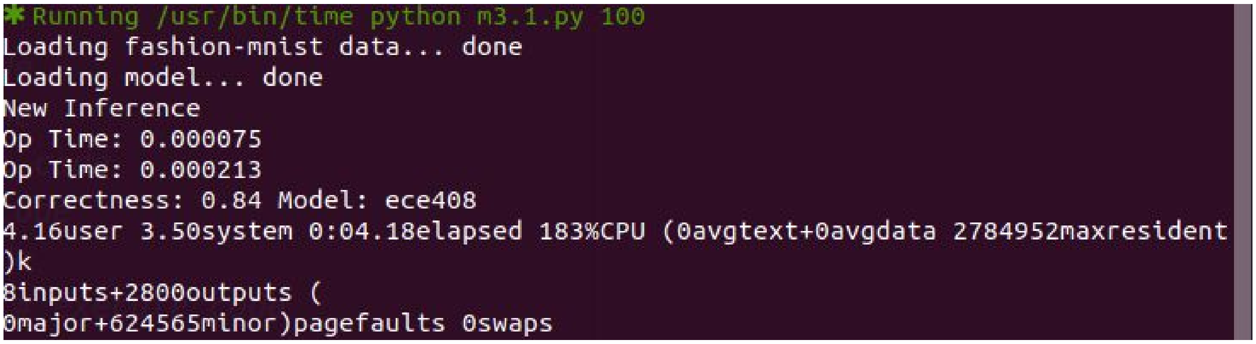
Default: 10,000



```
Op Time: 2.437733
Op Time: 7.488936
Correctness: 0.8397 Model: ece408
15.27user 4.59system 0:11.51elapsed 172%CPU (0avgtext+0avgdata 1617608maxresident)k
```

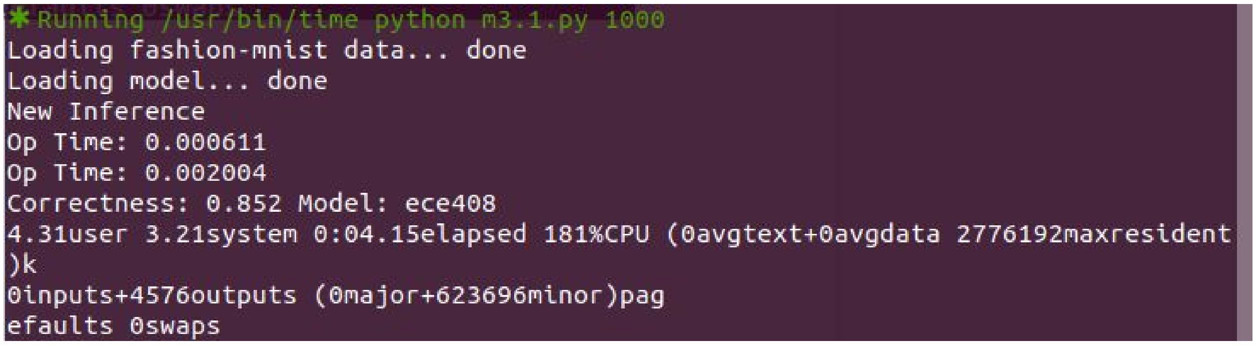
Milestone 3

Run #1: 100



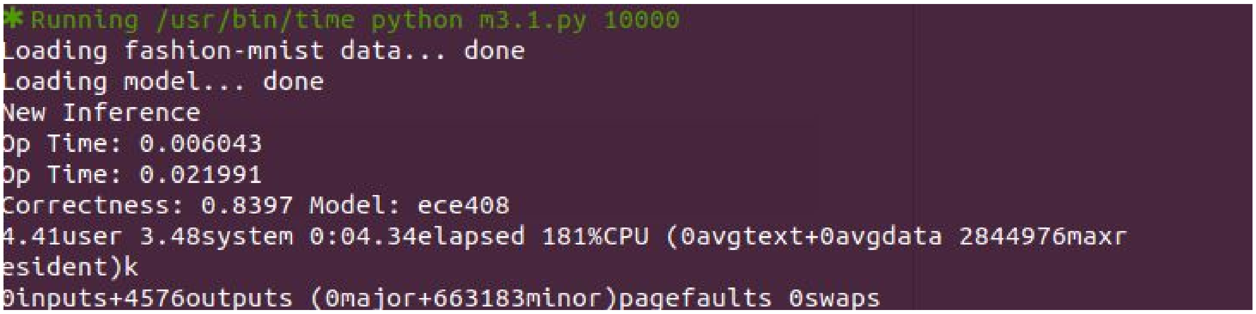
```
* Running /usr/bin/time python m3.1.py 100
Loading fashion-mnist data... done
Loading model... done
New Inference
Op Time: 0.000075
Op Time: 0.000213
Correctness: 0.84 Model: ece408
4.16user 3.50system 0:04.18elapsed 183%CPU (0avgtext+0avgdata 2784952maxresident
)k
8inputs+2800outputs (
0major+624565minor)pagefaults 0swaps
```

Run #2: 1,000



```
✱ Running /usr/bin/time python m3.1.py 1000
Loading fashion-mnist data... done
Loading model... done
New Inference
Op Time: 0.000611
Op Time: 0.002004
Correctness: 0.852 Model: ece408
4.31user 3.21system 0:04.15elapsed 181%CPU (0avgtext+0avgdata 2776192maxresident
)k
0inputs+4576outputs (0major+623696minor)pag
efaults 0swaps
```

Default: 10,000



```
✱ Running /usr/bin/time python m3.1.py 10000
Loading fashion-mnist data... done
Loading model... done
New Inference
Op Time: 0.006043
Op Time: 0.021991
Correctness: 0.8397 Model: ece408
4.41user 3.48system 0:04.34elapsed 181%CPU (0avgtext+0avgdata 2844976maxr
esident)k
0inputs+4576outputs (0major+663183minor)pagefaults 0swaps
```

MILESTONE 4

Kernels in constant memory optimization:

In this optimization we essentially put all the kernels in constant memory instead of fetching them from global memory each time. This sped up execution by a small amount because the gpu no longer needed to wait for global memory each time and could instead get from the far faster constant memory. In the nvprof output we can see that a very large portion of the time is spent copying memory from the host to the device. This makes sense since there is a lot of data to copy like the input, output, and const kernel memory. Everything else is fairly insignificant in terms of time used. The computation looks to have taken less time than the copying, which says something about what we learned in class about how GPU's operation.

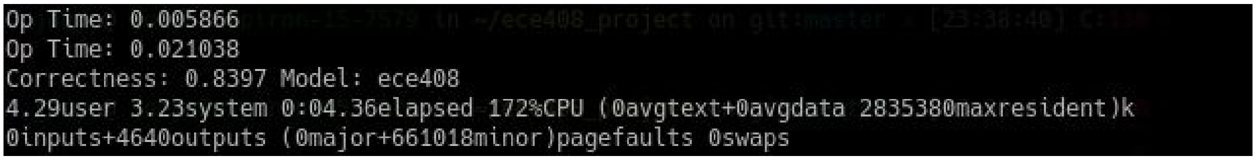
NVPROF output:

```
✱ Running nvprof python m4.1.py
Loading fashion-mnist data... done
==282== NVPROF is profiling process 282, command: python m4.1.py
Loading model... done
New Inference
Op Time: 0.005984
Op Time: 0.021129
Correctness: 0.8397 Model: ece408
==282== Profiling application: python m4.1.py
==282== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
```

```
 GPU activities:   52.19%  26.955ms         2  13.477ms  5.8940ms  21.061ms
mxnet::op::forward_kernel(float*, float const *, float const *, int, int, int, int, int, int)
                   32.50%  16.785ms        20  839.25us  1.1200us  16.367ms  [CUDA memcpy HtoD]
                    4.83%  2.4969ms         2  1.2484ms  22.624us  2.4743ms
volta_sgemm_32x128_tn
                    4.68%  2.4146ms         2  1.2073ms  732.92us  1.6817ms  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=4, float>, float>,
mshadow::expr::Plan<mshadow::expr::BinaryMapExp<mshadow::op::mul,
mshadow::expr::ScalarExp<float>, mshadow::Tensor<mshadow::gpu, int=4, float>, float, int=1>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=4, int)
                    3.15%  1.6250ms         2  812.49us  22.207us  1.6028ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
                    2.04%  1.0548ms         1  1.0548ms  1.0548ms  1.0548ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
                    0.31%  158.30us         1  158.30us  158.30us  158.30us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
                    0.15%  75.103us         1  75.103us  75.103us  75.103us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                    0.05%  27.808us        13  2.1390us  1.1840us  6.4960us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                    0.05%  24.288us         2  12.144us  2.5920us  21.696us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
```

```
                    0.02%  11.295us        10  1.1290us     992ns  1.6320us  [CUDA memset]
                    0.01%  5.9840us         2  2.9920us  2.9120us  3.0720us  [CUDA memcpy DtoD]
                    0.01%  5.4720us         1  5.4720us  5.4720us  5.4720us  [CUDA memcpy DtoH]
                    0.01%  4.6720us         1  4.6720us  4.6720us  4.6720us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
      API calls:   42.32%  3.00169s        22  136.44ms  14.044us  1.53483s
cudaStreamCreateWithFlags
                   34.35%  2.43651s        22  110.75ms  108.17us  2.43105s  cudaMemGetInfo
20.99%  1.48869s        18  82.705ms     875ns  396.71ms  cudaFree
                    0.71%  50.398ms       912  55.261us     307ns  36.773ms  cudaFuncSetAttribute
                    0.48%  34.330ms         9  3.8145ms  17.808us  16.514ms  cudaMemcpy2DAsync
                    0.41%  29.389ms         6  4.8981ms  3.7270us  21.061ms  cudaDeviceSynchronize
                    0.28%  19.739ms       216  91.383us     895ns  8.7924ms
cudaEventCreateWithFlags
                    0.17%  11.965ms        66  181.29us  5.4460us  1.7272ms  cudaMalloc
                    0.11%  7.9549ms         4  1.9887ms  470.49us  3.3376ms
cudaGetDeviceProperties
                    0.06%  4.4829ms        29  154.58us  2.9980us  2.1478ms  cudaStreamSynchronize
                    0.04%  2.5323ms       375  6.7520us     272ns  333.39us  cuDeviceGetAttribute
                    0.01%  787.82us         2  393.91us  84.316us  703.50us  cudaHostAlloc
                    0.01%  669.10us         4  167.27us  92.829us  276.86us  cuDeviceTotalMem
                    0.01%  624.88us        27  23.143us  8.5620us  64.383us  cudaLaunchKernel
                    0.01%  566.50us         4  141.62us  76.127us  220.07us  cudaStreamCreate
                    0.01%  470.95us        12  39.246us  8.0500us  86.436us  cudaMemcpy
                    0.00%  325.50us        10  32.550us  9.3450us  112.35us  cudaMemsetAsync
                    0.00%  293.17us       202  1.4510us     560ns  4.8010us  cudaDeviceGetAttribute
                    0.00%  274.81us         4  68.703us  45.592us  100.63us  cuDeviceGetName
                    0.00%  238.90us         8  29.862us  14.068us  71.035us
cudaStreamCreateWithPriority
                    0.00%  156.58us        29  5.3990us  1.0770us  16.726us  cudaSetDevice
                    0.00%  118.89us       557     213ns      79ns     771ns  cudaGetLastError
                    0.00%  86.434us         2  43.217us  37.954us  48.480us  cudaMemcpyToSymbol
                    0.00%  65.077us         4  16.269us  1.8870us  52.832us  cudaEventRecord
                    0.00%  43.422us        18  2.4120us     600ns  4.2970us  cudaGetDevice
                    0.00%  27.094us         6  4.5150us  1.3760us  11.713us  cudaEventCreate
                    0.00%  9.5680us         2  4.7840us  3.7110us  5.8570us  cudaEventQuery
                    0.00%  7.5360us         2  3.7680us  2.5570us  4.9790us
cudaHostGetDevicePointer
                    0.00%  6.4860us        20     324ns     110ns     657ns  cudaPeekAtLastError
```

```
                0.00%  6.4510us        6  1.0750us     551ns  2.3380us  cuDeviceGetCount
                0.00%  5.9450us        2  2.9720us  1.5960us  4.3490us
cudaDeviceGetStreamPriorityRange
                0.00%  4.6490us        5     929ns     418ns  1.5200us  cuDeviceGet
                0.00%  3.9440us        3  1.3140us     779ns  2.3110us  cuInit
                0.00%  3.7140us        1  3.7140us  3.7140us  3.7140us  cuDeviceGetPCIBusId
                0.00%  2.4030us        4     600ns     322ns  1.2250us  cuDeviceGetUuid
                0.00%  2.3840us        4     596ns     295ns  1.0180us  cudaGetDeviceCount
                0.00%  1.7610us        3     587ns     317ns  1.1250us  cuDriverGetVersion
```



```
Op Time: 0.005866
Op Time: 0.021038
Correctness: 0.8397 Model: ece408
4.29user 3.23system 0:04.36elapsed 172%CPU (0avgtext+0avgdata 2835380maxresident)k
0inputs+4640outputs (0major+661018minor)pagefaults 0swaps
```

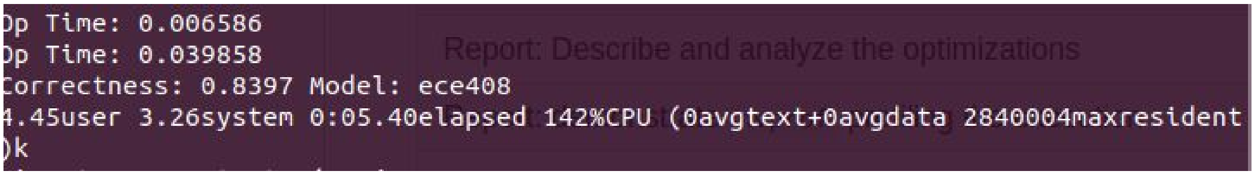
Shared memory convolution optimization:
In this optimization we used shared memory and tiled every image in order to try and get a speed up. However, it actually took longer and didn't save time perhaps because of the extra time it took to load into shared memory. Again in NVPROF output we can see that the most time is used copying all that data. However, it is significantly less than the copying for the constant memory optimization for some reason. For some reason though the algorithm took longer than the original, which maybe is because of extra floating point computation that had to be used in order to use shared memory and tiling.

NVPROF output:

```
✱ Running nvprof python m4.1.py
Loading fashion-mnist data... done
==283== NVPROF is profiling process 283, command: python m4.1.py
Loading model... done
New Inference
Op Time: 0.006688
Op Time: 0.039945
Correctness: 0.8397 Model: ece408
==283== Profiling application: python m4.1.py
==283== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   65.05%  46.549ms         2  23.274ms  6.6460ms  39.903ms
mxnet::op::forward_kernel(float*, float const *, float const *, int, int, int, int, int, int)
                   23.89%  17.098ms        20  854.90us  1.0870us  16.571ms  [CUDA memcpy HtoD]
                    3.50%  2.5054ms         2  1.2527ms  21.408us  2.4839ms
volta_sgemm_32x128_tn
```

```
                3.39%  2.4293ms         2  1.2147ms  738.84us  1.6905ms  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=4, float>, float>,
mshadow::expr::Plan<mshadow::expr::BinaryMapExp<mshadow::op::mul,
mshadow::expr::ScalarExp<float>, mshadow::Tensor<mshadow::gpu, int=4, float>, float, int=1>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=4, int)
                2.27%  1.6222ms         2  811.10us  21.952us  1.6002ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
                1.47%  1.0509ms         1  1.0509ms  1.0509ms  1.0509ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
                0.22%  158.33us         1  158.33us  158.33us  158.33us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
                0.10%  75.103us         1  75.103us  75.103us  75.103us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                0.04%  27.551us        13  2.1190us  1.1520us  6.4310us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                0.03%  23.808us         2  11.904us  2.4960us  21.312us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
                0.02%  11.775us        10  1.1770us     992ns  1.6320us  [CUDA memset]
                0.01%  7.9990us         1  7.9990us  7.9990us  7.9990us  [CUDA memcpy DtoH]
                0.01%  4.6400us         1  4.6400us  4.6400us  4.6400us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
      API calls:   43.63%  3.30590s        22  150.27ms  13.646us  1.65226s
cudaStreamCreateWithFlags
                   33.69%  2.55286s        22  116.04ms  90.912us  2.54790s  cudaMemGetInfo
                   21.22%  1.60798s        18  89.332ms     934ns  436.06ms  cudaFree
0.65%  49.010ms         6  8.1683ms  5.5220us  39.911ms  cudaDeviceSynchronize
                    0.46%  34.679ms         9  3.8532ms  35.671us  16.619ms  cudaMemcpy2DAsync
                    0.11%  8.0740ms        66  122.33us  6.4630us  1.0804ms  cudaMalloc
                    0.06%  4.9098ms        29  169.30us  3.0820us  2.2344ms  cudaStreamSynchronize
                    0.06%  4.7821ms         4  1.1955ms  594.51us  1.7482ms
cudaGetDeviceProperties
                    0.03%  2.4967ms       375  6.6570us     287ns  336.92us  cuDeviceGetAttribute
                    0.01%  1.0539ms       216  4.8780us     903ns  164.36us
cudaEventCreateWithFlags
                    0.01%  972.95us       912  1.0660us     308ns  28.289us  cudaFuncSetAttribute
                    0.01%  972.16us        10  97.215us  8.7890us  740.59us  cudaMemsetAsync
                    0.01%  753.49us         2  376.75us  30.463us  723.03us  cudaHostAlloc
                    0.01%  682.10us         4  170.53us  96.592us  280.71us  cuDeviceTotalMem
                    0.01%  589.57us         4  147.39us  96.650us  231.88us  cudaStreamCreate
                    0.01%  531.84us        27  19.697us  8.1210us  59.889us  cudaLaunchKernel
                    0.00%  310.86us        12  25.905us  9.2750us  65.413us  cudaMemcpy
                    0.00%  287.07us         4  71.766us  47.213us  106.39us  cuDeviceGetName
                    0.00%  188.34us        29  6.4940us  1.0100us  37.831us  cudaSetDevice
                    0.00%  172.83us       202     855ns     566ns  2.3720us  cudaDeviceGetAttribute
                    0.00%  146.59us         8  18.323us  9.6010us  53.927us
cudaStreamCreateWithPriority
                    0.00%  66.765us       557     119ns      75ns     541ns  cudaGetLastError
                    0.00%  45.648us         6  7.6080us  1.3970us  34.856us  cudaEventCreate
                    0.00%  30.209us        18  1.6780us     610ns  3.9380us  cudaGetDevice
                    0.00%  13.473us         4  3.3680us  1.7230us  4.4740us  cudaEventRecord
                    0.00%  8.0900us         2  4.0450us  3.5980us  4.4920us  cudaEventQuery
                    0.00%  6.4420us         6  1.0730us     543ns  2.5680us  cuDeviceGetCount
                    0.00%  5.4950us        20     274ns     154ns     558ns  cudaPeekAtLastError
                    0.00%  5.1810us         2  2.5900us  2.3190us  2.8620us
cudaHostGetDevicePointer
                    0.00%  4.5580us         5     911ns     508ns  1.6070us  cuDeviceGet
                    0.00%  4.4850us         1  4.4850us  4.4850us  4.4850us  cuDeviceGetPCIBusId
                    0.00%  4.4090us         3  1.4690us     930ns  2.3420us  cuInit
                    0.00%  3.4450us         2  1.7220us  1.6080us  1.8370us
cudaDeviceGetStreamPriorityRange
                    0.00%  2.7260us         4     681ns     346ns  1.2350us  cuDeviceGetUuid
```

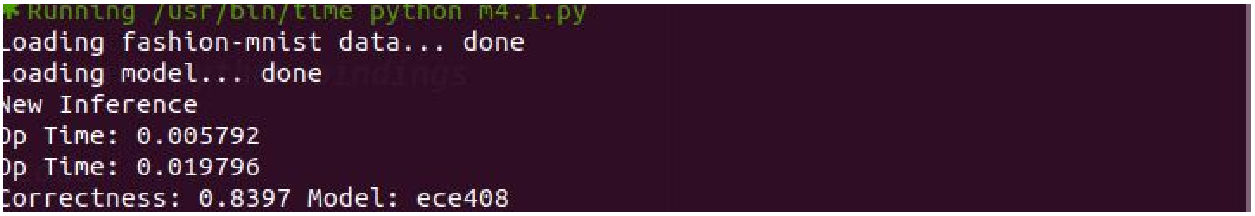
```
                0.00%  2.2490us         4     562ns     279ns     900ns  cudaGetDeviceCount
                0.00%  1.9590us         3     653ns     367ns  1.1500us  cuDriverGetVersion
```



```
Op Time: 0.006586
Op Time: 0.039858
Correctness: 0.8397 Model: ece408
4.45user 3.26system 0:05.40elapsed 142%CPU (0avgtext+0avgdata 2840004maxresident
)k
```

Double Buffer Optimization

In this trial we implemented double buffering to reduce the number of syncthread calls (previously we had 2 - one to ensure data is loaded, the other to ensure data is consumed). In double buffering, pointers to shared memory alternate for each iteration, eliminating the inner loop syncthreads call and visibly reducing the operation time by a fraction of a millisecond. Unfortunately, there were some issues setting up NVVP so further analysis is not present but the matter will most likely be resolved by next checkpoint. For now, we have attached the NVPROF output.



```
✱ Running /usr/bin/time python m4.1.py
Loading fashion-mnist data... done
Loading model... done
New Inference
Op Time: 0.005792
Op Time: 0.019796
Correctness: 0.8397 Model: ece408
```

NVPROF output:

```
✱ Running nvprof python m4.1.py
Loading fashion-mnist data... done
==283== NVPROF is profiling process 283, command: python m4.1.py
Loading model... done
New Inference
Op Time: 0.005886
Op Time: 0.019878
Correctness: 0.8397 Model: ece408
==283== Profiling application: python m4.1.py
==283== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   51.64%  25.630ms         2  12.815ms  5.8105ms  19.820ms
mxnet::op::forward_kernel(float*, float const *, float const *, int, int, int, int, int, int)
                   32.97%  16.367ms        20  818.35us  1.1200us  15.989ms  [CUDA memcpy HtoD]
                    4.77%  2.3661ms         2  1.1831ms  722.59us  1.6435ms  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=4, float>, float>,
mshadow::expr::Plan<mshadow::expr::BinaryMapExp<mshadow::op::mul,
mshadow::expr::ScalarExp<float>, mshadow::Tensor<mshadow::gpu, int=4, float>, float, int=1>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=4, int)
                4.66%  2.3113ms         2  1.1557ms  21.472us  2.2898ms
volta_sgemm_32x128_tn
                3.25%  1.6121ms         2  806.04us  21.824us  1.5903ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
                2.10%  1.0428ms         1  1.0428ms  1.0428ms  1.0428ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
                0.31%  152.83us         1  152.83us  152.83us  152.83us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
                0.15%  75.264us         1  75.264us  75.264us  75.264us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                0.06%  27.871us        13  2.1430us  1.1840us  6.4320us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                0.05%  23.680us         2  11.840us  2.5600us  21.120us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
                0.02%  11.168us        10  1.1160us     992ns  1.6320us  [CUDA memset]
                0.01%  5.7600us         1  5.7600us  5.7600us  5.7600us  [CUDA memcpy DtoH]
                0.01%  5.1510us         2  2.5750us  2.4320us  2.7190us  [CUDA memcpy DtoD]
                0.01%  5.0560us         1  5.0560us  5.0560us  5.0560us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
      API calls:   41.20%  3.35913s        22  152.69ms  98.856us  3.35334s  cudaMemGetInfo
                   37.94%  3.09287s        22  140.58ms  14.139us  1.56727s
cudaStreamCreateWithFlags
19.24%  1.56837s        18  87.132ms     839ns  430.35ms  cudaFree
                    0.41%  33.555ms         9  3.7283ms  18.372us  16.181ms  cudaMemcpy2DAsync
                    0.34%  28.018ms         6  4.6696ms  2.7620us  19.821ms  cudaDeviceSynchronize
                    0.32%  26.236ms       912  28.767us     312ns  7.5358ms  cudaFuncSetAttribute
                    0.22%  17.782ms        66  269.42us  5.8580us  5.9865ms  cudaMalloc
                    0.10%  7.9502ms       216  36.806us     895ns  5.4752ms
cudaEventCreateWithFlags
                    0.06%  4.9316ms         4  1.2329ms  424.58us  1.8548ms
cudaGetDeviceProperties
                    0.05%  4.3637ms        29  150.47us  2.5680us  2.0465ms  cudaStreamSynchronize
                    0.05%  4.2113ms       375  11.230us     286ns  1.8498ms  cuDeviceGetAttribute
                    0.01%  962.27us         8  120.28us  13.671us  738.47us
cudaStreamCreateWithPriority
                    0.01%  748.26us         2  374.13us  48.475us  699.79us  cudaHostAlloc
                    0.01%  644.39us         4  161.10us  92.428us  273.52us  cuDeviceTotalMem
                    0.01%  621.00us        27  23.000us  8.8280us  57.041us  cudaLaunchKernel
                    0.01%  577.57us         4  144.39us  75.965us  229.16us  cudaStreamCreate
                    0.01%  430.78us        12  35.898us  5.9940us  88.814us  cudaMemcpy
                    0.00%  311.63us        10  31.162us  8.5100us  101.64us  cudaMemsetAsync
                    0.00%  290.29us         4  72.571us  47.064us  104.55us  cuDeviceGetName
                    0.00%  289.23us       202  1.4310us     567ns  3.9070us  cudaDeviceGetAttribute
                    0.00%  152.57us        29  5.2610us  1.1310us  16.778us  cudaSetDevice
                    0.00%  114.50us       557     205ns      76ns  9.6110us  cudaGetLastError
                    0.00%  76.428us         4  19.107us  2.0780us  63.771us  cudaEventRecord
                    0.00%  73.877us         2  36.938us  33.464us  40.413us  cudaMemcpyToSymbol
                    0.00%  42.154us        18  2.3410us     594ns  4.1290us  cudaGetDevice
                    0.00%  33.572us         2  16.786us  4.9530us  28.619us
cudaHostGetDevicePointer
                    0.00%  26.454us         6  4.4090us  1.3730us  8.9730us  cudaEventCreate
                    0.00%  6.6290us        20     331ns     124ns     651ns  cudaPeekAtLastError
                    0.00%  6.1630us         2  3.0810us  2.7760us  3.3870us  cudaEventQuery
                    0.00%  5.8730us         2  2.9360us  1.6680us  4.2050us
cudaDeviceGetStreamPriorityRange
                    0.00%  5.4900us         6     915ns     331ns  1.9390us  cuDeviceGetCount
                    0.00%  4.5650us         1  4.5650us  4.5650us  4.5650us  cuDeviceGetPCIBusId
                    0.00%  4.4780us         5     895ns     467ns  1.6250us  cuDeviceGet
                    0.00%  4.4700us         3  1.4900us     881ns  2.4290us  cuInit
```

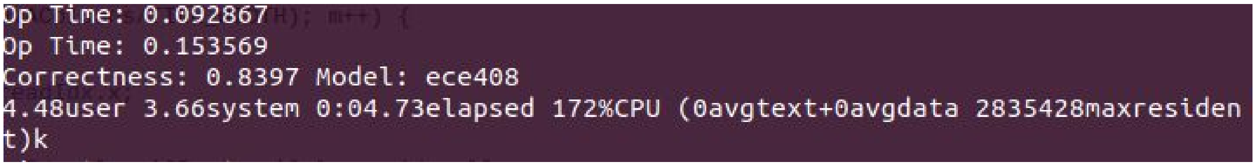
```
0.00%  2.6610us        4     665ns     354ns  1.2080us  cuDeviceGetUuid
0.00%  2.3770us        4     594ns     189ns  1.3370us  cudaGetDeviceCount
0.00%  2.1340us        3     711ns     410ns  1.1370us  cuDriverGetVersion
```

FINAL MILESTONE

****NOTE: NVVP still did not work, was not able to downgrade from v10.01 to 10.0 successfully, so we were unable to produce graphs that could provide more insight on kernel performances**

Optimization 4: Unrolling and GEMM

In this optimization, we prepare an expanded/unrolled input feature map (X_unrolled) before performing Matrix Multiplication. In the sequential algorithm described in the textbook, the kernel for unrolling the input feature map requires placing one input feature element for every output feature map element, repeating for filtering, etc. The design utilizes a memory write coalescing pattern as every output is derived from the input feature map elements.



```
Op Time: 0.092867
Op Time: 0.153569
Correctness: 0.8397 Model: ece408
4.48user 3.66system 0:04.73elapsed 172%CPU (0avgtext+0avgdata 2835428maxresiden
t)k
```

Without the NVVP visualizer to shed light on whether the launched kernels (unroll and MM) were compute or memory-bound, we suspect that the major slowdown (about 3ms compared to baseline) was due to excessive global memory accesses. Caching or integrating shared memory could alleviate these drawbacks.

NVPROF Output:

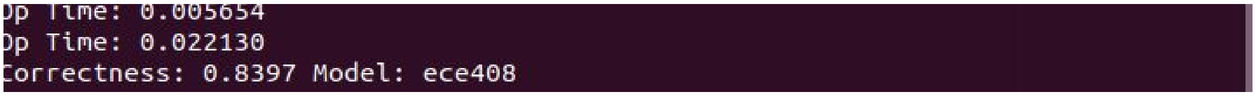
```
✱ Running nvprof python final.py
Loading fashion-mnist data...
done
Loading model...
==286== NVPROF is profiling process 286, command: python final.py
done
New Inference
Op Time: 0.133347
Op Time: 0.163717
Correctness: 0.8397 Model: ece408
==286== Profiling application: python final.py
==286== Profiling result:
Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   65.39%  146.22ms     20000  7.3110us  3.9680us  1.1944ms
mxnet::op::matrixMultiplyShared(float*, float*, float*, int, int, int)
```

```
               23.27%  52.028ms     20000  2.6010us  2.3360us  17.055us
mxnet::op::unrollKernel(float*, int, float*, int, int, int, int)
                7.61%  17.008ms        20  850.38us  1.0880us  16.597ms  [CUDA memcpy HtoD]
                1.10%  2.4535ms         2  1.2267ms  20.256us  2.4332ms
volta_sgemm_32x128_tn
                1.08%  2.4128ms         2  1.2064ms  733.91us  1.6789ms  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=4, float>, float>,
mshadow::expr::Plan<mshadow::expr::BinaryMapExp<mshadow::op::mul,
mshadow::expr::ScalarExp<float>, mshadow::Tensor<mshadow::gpu, int=4, float>, float, int=1>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=4, int)
                0.73%  1.6260ms         2  812.98us  22.400us  1.6036ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
                0.70%  1.5566ms         1  1.5566ms  1.5566ms  1.5566ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
                0.07%  156.61us         1  156.61us  156.61us  156.61us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
                0.03%  68.575us         1  68.575us  68.575us  68.575us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                0.01%  28.096us        13  2.1610us  1.1840us  6.5920us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                0.01%  23.807us         2  11.903us  2.3030us  21.504us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
```

```
                0.01%  11.456us        10  1.1450us     960ns  1.8560us  [CUDA memset]
                0.00%  5.8560us         1  5.8560us  5.8560us  5.8560us  [CUDA memcpy DtoH]
                0.00%  4.3840us         1  4.3840us  4.3840us  4.3840us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
      API calls:   44.10%  3.70292s        22  168.31ms  14.343us  1.87643s
cudaStreamCreateWithFlags
               31.46%  2.64196s        22  120.09ms  90.665us  2.63747s  cudaMemGetInfo
19.91%  1.67167s        20  83.583ms     920ns  436.83ms  cudaFree
                3.14%  263.81ms     40025  6.5910us  4.9130us  1.1939ms  cudaLaunchKernel
                0.41%  34.843ms         9  3.8715ms  26.934us  16.749ms  cudaMemcpy2DAsync
                0.37%  31.215ms       216  144.51us     930ns  18.520ms
cudaEventCreateWithFlags
                0.25%  20.965ms       912  22.988us     311ns  5.1608ms  cudaFuncSetAttribute
                0.10%  8.4647ms        68  124.48us  7.2740us  1.1165ms  cudaMalloc
                0.07%  6.2840ms        29  216.69us  3.5600us  3.2043ms  cudaStreamSynchronize
                0.06%  4.7354ms         4  1.1839ms  438.36us  1.7484ms
cudaGetDeviceProperties
                0.03%  2.5445ms         6  424.08us  2.2310us  1.6818ms  cudaDeviceSynchronize
                0.03%  2.4094ms       375  6.4250us     290ns  415.58us  cuDeviceGetAttribute
                0.01%  1.0017ms         8  125.22us  14.591us  795.20us
cudaStreamCreateWithPriority
                0.01%  828.45us         2  414.22us  47.071us  781.38us  cudaHostAlloc
                0.01%  792.39us        10  79.238us  9.9960us  510.27us  cudaMemsetAsync
                0.01%  728.70us        12  60.725us  14.577us  174.01us  cudaMemcpy
                0.01%  589.63us         4  147.41us  101.34us  195.30us  cudaStreamCreate
                0.01%  494.55us         4  123.64us  97.564us  155.86us  cuDeviceTotalMem
                0.00%  288.68us       202  1.4290us     573ns  16.813us  cudaDeviceGetAttribute
                0.00%  236.07us         4  59.018us  41.200us  73.722us  cuDeviceGetName
                0.00%  165.70us        29  5.7130us     965ns  31.410us  cudaSetDevice
                0.00%  103.12us       557     185ns      77ns     768ns  cudaGetLastError
                0.00%  51.356us        18  2.8530us     596ns  7.7130us  cudaGetDevice
                0.00%  34.639us         6  5.7730us  1.7620us  13.743us  cudaEventCreate
                0.00%  26.227us         2  13.113us  4.6040us  21.623us
cudaHostGetDevicePointer
                0.00%  17.961us         4  4.4900us  2.5520us  7.4750us  cudaEventRecord
                0.00%  8.3790us         2  4.1890us  3.4760us  4.9030us  cudaEventQuery
                0.00%  6.0700us         2  3.0350us  1.8610us  4.2090us
cudaDeviceGetStreamPriorityRange
                0.00%  5.9790us        20     298ns     115ns     561ns  cudaPeekAtLastError
                0.00%  5.1740us        6     862ns     410ns  2.2260us  cuDeviceGetCount
                0.00%  3.7980us        3  1.2660us     953ns  1.6550us  cuInit
                0.00%  3.6780us        1  3.6780us  3.6780us  3.6780us  cuDeviceGetPCIBusId
                0.00%  3.2200us        5     644ns     347ns  1.1190us  cuDeviceGet
                0.00%  2.6480us        4     662ns     313ns     999ns  cudaGetDeviceCount
                0.00%  2.3850us        4     596ns     373ns  1.0720us  cuDeviceGetUuid
                0.00%  1.5870us        3     529ns     367ns     750ns  cuDriverGetVersion
```

Optimization 5: Unroll and Restrict

We inserted #pragma unroll before the loops in the convolution kernel to lessen the load on the processor. Instead of checking the conditional inside the loop, the preprocessor directive essentially skips it and replaces the loop with the full evaluation trip count number of times. The __restrict__ tag resembles the familiar “volatile” tag seen in embedded programming in that it instructs the compiler to make various optimizations, specifically for reducing pointer aliasing. Restrict was applied to the input feature maps, output feature maps, and the weight matrices.



```
Op Time: 0.005654
Op Time: 0.022130
Correctness: 0.8397 Model: ece408
```

The results proved to be fruitful, shaving off fractions of a millisecond off of the GPU baseline seen a few weeks ago.

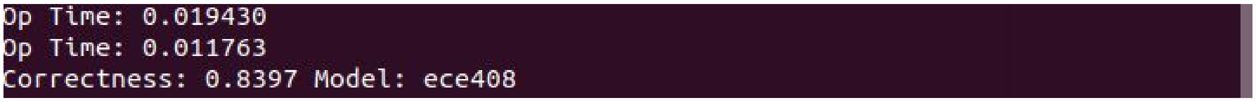
NVPROF Output:

```
✱ Running nvprof python final.py
Loading fashion-mnist data...
done
Loading model...
==286== NVPROF is profiling process 286, command: python final.py
done
New Inference
Op Time: 0.133347
Op Time: 0.163717
Correctness: 0.8397 Model: ece408
==286== Profiling application: python final.py
==286== Profiling result:
Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   65.39%  146.22ms     20000  7.3110us  3.9680us  1.1944ms
mxnet::op::matrixMultiplyShared(float*, float*, float*, int, int, int)
                23.27%  52.028ms     20000  2.6010us  2.3360us  17.055us
mxnet::op::unrollKernel(float*, int, float*, int, int, int, int)
                7.61%  17.008ms        20  850.38us  1.0880us  16.597ms  [CUDA memcpy HtoD]
                1.10%  2.4535ms         2  1.2267ms  20.256us  2.4332ms
volta_sgemm_32x128_tn
                1.08%  2.4128ms         2  1.2064ms  733.91us  1.6789ms  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=4, float>, float>,
mshadow::expr::Plan<mshadow::expr::BinaryMapExp<mshadow::op::mul,
mshadow::expr::ScalarExp<float>, mshadow::Tensor<mshadow::gpu, int=4, float>, float, int=1>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=4, int)
                0.73%  1.6260ms         2  812.98us  22.400us  1.6036ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
                0.70%  1.5566ms         1  1.5566ms  1.5566ms  1.5566ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
                0.07%  156.61us         1  156.61us  156.61us  156.61us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
                0.03%  68.575us         1  68.575us  68.575us  68.575us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                0.01%  28.096us        13  2.1610us  1.1840us  6.5920us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                0.01%  23.807us         2  11.903us  2.3030us  21.504us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
                0.01%  11.456us        10  1.1450us     960ns  1.8560us  [CUDA memset]
                0.00%  5.8560us         1  5.8560us  5.8560us  5.8560us  [CUDA memcpy DtoH]
                0.00%  4.3840us         1  4.3840us  4.3840us  4.3840us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
     API calls:   44.10%  3.70292s        22  168.31ms  14.343us  1.87643s
cudaStreamCreateWithFlags
               31.46%  2.64196s        22  120.09ms  90.665us  2.63747s  cudaMemGetInfo
19.91%  1.67167s        20  83.583ms     920ns  436.83ms  cudaFree
                3.14%  263.81ms     40025  6.5910us  4.9130us  1.1939ms  cudaLaunchKernel
                0.41%  34.843ms         9  3.8715ms  26.934us  16.749ms  cudaMemcpy2DAsync
                0.37%  31.215ms       216  144.51us     930ns  18.520ms
cudaEventCreateWithFlags
                0.25%  20.965ms       912  22.988us     311ns  5.1608ms  cudaFuncSetAttribute
                0.10%  8.4647ms        68  124.48us  7.2740us  1.1165ms  cudaMalloc
                0.07%  6.2840ms        29  216.69us  3.5600us  3.2043ms  cudaStreamSynchronize
                0.06%  4.7354ms         4  1.1839ms  438.36us  1.7484ms
cudaGetDeviceProperties
                0.03%  2.5445ms         6  424.08us  2.2310us  1.6818ms  cudaDeviceSynchronize
                0.03%  2.4094ms       375  6.4250us     290ns  415.58us  cuDeviceGetAttribute
                0.01%  1.0017ms         8  125.22us  14.591us  795.20us
cudaStreamCreateWithPriority
                0.01%  828.45us         2  414.22us  47.071us  781.38us  cudaHostAlloc
                0.01%  792.39us        10  79.238us  9.9960us  510.27us  cudaMemsetAsync
                0.01%  728.70us        12  60.725us  14.577us  174.01us  cudaMemcpy
                0.01%  589.63us         4  147.41us  101.34us  195.30us  cudaStreamCreate
                0.01%  494.55us         4  123.64us  97.564us  155.86us  cuDeviceTotalMem
                0.00%  288.68us       202  1.4290us     573ns  16.813us  cudaDeviceGetAttribute
                0.00%  236.07us         4  59.018us  41.200us  73.722us  cuDeviceGetName
                0.00%  165.70us        29  5.7130us     965ns  31.410us  cudaSetDevice
                0.00%  103.12us       557     185ns      77ns     768ns  cudaGetLastError
                0.00%  51.356us        18  2.8530us     596ns  7.7130us  cudaGetDevice
                0.00%  34.639us         6  5.7730us  1.7620us  13.743us  cudaEventCreate
                0.00%  26.227us         2  13.113us  4.6040us  21.623us
cudaHostGetDevicePointer
                0.00%  17.961us         4  4.4900us  2.5520us  7.4750us  cudaEventRecord
                0.00%  8.3790us         2  4.1890us  3.4760us  4.9030us  cudaEventQuery
                0.00%  6.0700us         2  3.0350us  1.8610us  4.2090us
cudaDeviceGetStreamPriorityRange
                0.00%  5.9790us        20     298ns     115ns     561ns  cudaPeekAtLastError
                0.00%  5.1740us         6     862ns     410ns  2.2260us  cuDeviceGetCount
                0.00%  3.7980us         3  1.2660us     953ns  1.6550us  cuInit
```

```
        0.00%  3.6780us         1  3.6780us  3.6780us  3.6780us  cuDeviceGetPCIBusId
        0.00%  3.2200us         5     644ns     347ns  1.1190us  cuDeviceGet
        0.00%  2.6480us         4     662ns     313ns     999ns  cudaGetDeviceCount
        0.00%  2.3850us         4     596ns     373ns  1.0720us  cuDeviceGetUuid
        0.00%  1.5870us         3     529ns     367ns     750ns  cuDriverGetVersion
```

Optimization 6: Parallelism in Input

In this optimization, we rearranged the grid dimensions to parallelize the input. Logic within the standard matrix multiply kernel was also reworked to streamline the populating of the subtile arrays. We theorize to see a reduction in running time since the MatrixMultiply kernel should only be executed once for every forward pass unlike previous implementations. The runtime optimization is not reflected in the optime but is what we would expect if the visualizer and timeline successfully ran.



```
Op Time: 0.019430
Op Time: 0.011763
Correctness: 0.8397 Model: ece408
```

Possible interpretations of how the optime is slower than the baseline include global memory loads and stores or thread utilization inefficiency.

NVPROF Output:

```
✱ Running nvprof python final.py
Loading fashion-mnist data...
done
Loading model...
==287== NVPROF is profiling process 287, command: python final.py
done
New Inference
Op Time: 0.019758
Op Time: 0.011852
Correctness: 0.8397 Model: ece408
==287== Profiling application: python final.py
==287== Profiling result:
            Type  Time(%)      Time     Calls       Avg       Min       Max  Name
 GPU activities:   56.21%  31.564ms         2  15.782ms  11.836ms  19.728ms
mxnet::op::matrixMultiplyShared(float*, float*, float*, int, int, int, int, int, int, int, int, int, int)
                   29.69%  16.673ms        20  833.65us  1.1200us  16.264ms  [CUDA memcpy HtoD]
                    4.47%  2.5095ms         2  1.2548ms  21.152us  2.4884ms
volta_sgemm_32x128_tn
                    4.31%  2.4197ms         2  1.2098ms  733.85us  1.6858ms  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=4, float>, float>,
mshadow::expr::Plan<mshadow::expr::BinaryMapExp<mshadow::op::mul,
mshadow::expr::ScalarExp<float>, mshadow::Tensor<mshadow::gpu, int=4, float>, float, int=1>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=4, int)
                    2.89%  1.6236ms         2  811.80us  22.400us  1.6012ms  void
op_generic_tensor_kernel<int=2, float, float, float, int=256, cudnnGenericOp_t=7,
cudnnNanPropagation_t=0, cudnnDimOrder_t=0, int=1>(cudnnTensorStruct, float*,
cudnnTensorStruct, float const *, cudnnTensorStruct, float const *, float, float, float, float,
dimArray, reducedDivisorArray)
                    1.88%  1.0563ms         1  1.0563ms  1.0563ms  1.0563ms  void
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>(cudnnTensorStruct, float const *,
cudnn::detail::pooling_fw_4d_kernel<float, float, cudnn::detail::maxpooling_func<float,
cudnnNanPropagation_t=0>, int=0, bool=0>, cudnnTensorStruct*, cudnnPoolingStruct, float,
cudnnPoolingStruct, int, cudnn::reduced_divisor, float)
                    0.28%  157.28us         1  157.28us  157.28us  157.28us  void
mshadow::cuda::MapPlanLargeKernel<mshadow::sv::saveto, int=8, int=1024,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2, int)
                    0.13%  75.200us         1  75.200us  75.200us  75.200us  void
mshadow::cuda::SoftmaxKernel<int=8, float,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>>(mshadow::gpu,
int=2, unsigned int)
                    0.05%  27.936us        13  2.1480us  1.1840us  6.4960us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ScalarExp<float>, float>>(mshadow::gpu, unsigned int,
mshadow::Shape<int=2>, int=2)
                    0.04%  24.096us         2  12.048us  2.5600us  21.536us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::plusto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::Broadcast1DExp<mshadow::Tensor<mshadow::gpu,
int=1, float>, float, int=2, int=1>, float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>,
int=2)
                    0.02%  12.000us        10  1.2000us     992ns  2.1440us  [CUDA memset]
                    0.01%  5.6000us         1  5.6000us  5.6000us  5.6000us  [CUDA memcpy DtoH]
                    0.01%  5.0240us         1  5.0240us  5.0240us  5.0240us  void
mshadow::cuda::MapPlanKernel<mshadow::sv::saveto, int=8,
mshadow::expr::Plan<mshadow::Tensor<mshadow::gpu, int=2, float>, float>,
mshadow::expr::Plan<mshadow::expr::ReduceWithAxisExp<mshadow::red::maximum,
mshadow::Tensor<mshadow::gpu, int=3, float>, float, int=3, bool=1, int=2>,
float>>(mshadow::gpu, unsigned int, mshadow::Shape<int=2>, int=2)
      API calls:   41.12%  3.00757s        22  136.71ms  14.581us  1.57537s
cudaStreamCreateWithFlags
                   33.95%  2.48260s        22  112.85ms  88.809us  2.47806s  cudaMemGetInfo
                   21.65%  1.58341s        18  87.967ms     813ns  420.29ms  cudaFree
0.93%  68.180ms       912  74.758us     297ns  18.738ms  cudaFuncSetAttribute
                    0.91%  66.497ms        12  5.5414ms  7.7170us  66.056ms  cudaMemcpy
                    0.47%  34.106ms         9  3.7895ms  17.776us  16.410ms  cudaMemcpy2DAsync
                    0.46%  34.003ms         6  5.6671ms  2.1500us  19.730ms  cudaDeviceSynchronize
                    0.22%  16.076ms        66  243.57us  5.7830us  9.7008ms  cudaMalloc
                    0.11%  7.7664ms         4  1.9416ms  1.7236ms  2.3508ms
cudaGetDeviceProperties
                    0.07%  5.1158ms        29  176.41us  1.8970us  2.2711ms  cudaStreamSynchronize
                    0.03%  2.4822ms       375  6.6190us     285ns  347.85us  cuDeviceGetAttribute
                    0.02%  1.7294ms       216  8.0060us     835ns  459.86us
cudaEventCreateWithFlags
                    0.01%  763.89us         2  381.95us  49.436us  714.46us  cudaHostAlloc
                    0.01%  667.90us         4  166.98us  104.59us  276.02us  cuDeviceTotalMem
                    0.01%  566.20us         4  141.55us  70.691us  248.26us  cudaStreamCreate
                    0.01%  456.47us        27  16.906us  8.0520us  49.044us  cudaLaunchKernel
                    0.00%  323.83us        10  32.383us  8.9510us  115.99us  cudaMemsetAsync
                    0.00%  305.77us       202  1.5130us     543ns  16.928us  cudaDeviceGetAttribute
                    0.00%  270.13us         4  67.531us  45.193us  103.56us  cuDeviceGetName
                    0.00%  245.61us         8  30.701us  14.094us  70.023us
cudaStreamCreateWithPriority
                    0.00%  141.95us        29  4.8940us     916ns  16.563us  cudaSetDevice
                    0.00%  105.95us       557     190ns      73ns  1.0240us  cudaGetLastError
                    0.00%  49.763us        18  2.7640us     564ns  4.8730us  cudaGetDevice
                    0.00%  37.737us         6  6.2890us  1.3810us  14.067us  cudaEventCreate
                    0.00%  27.918us         2  13.959us  4.8870us  23.031us
cudaHostGetDevicePointer
                    0.00%  16.013us         4  4.0030us  1.6100us  7.2130us  cudaEventRecord
                    0.00%  6.1760us         2  3.0880us  1.8100us  4.3660us
cudaDeviceGetStreamPriorityRange
                    0.00%  5.9720us         6     995ns     457ns  2.2870us  cuDeviceGetCount
                    0.00%  5.8710us         2  2.9350us  2.7600us  3.1110us  cudaEventQuery
                    0.00%  5.5170us        20     275ns     107ns     610ns  cudaPeekAtLastError
                    0.00%  5.0560us         5  1.0110us     405ns  2.2970us  cuDeviceGet
                    0.00%  4.7490us         3  1.5830us  1.0140us  2.6050us  cuInit
                    0.00%  3.7610us         1  3.7610us  3.7610us  3.7610us  cuDeviceGetPCIBusId
                    0.00%  2.5910us         4     647ns     342ns  1.3120us  cuDeviceGetUuid
                    0.00%  2.0910us         3     697ns     305ns  1.3920us  cuDriverGetVersion
```

```
    0.00%  1.8610us         4     465ns     213ns     764ns  cudaGetDeviceCount
```