NVIDIA cuDNN

Best Practices | NVIDIA Docs
List of Tables

Table 1. Average speed-up of unique cuDNN (version 8.3.0 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................6

Table 2. Average speed-up of unique cuDNN (version 8.2.4 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................7

Table 3. Average speed-up of unique cuDNN (version 8.2.2 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................7

Table 4. Average speed-up of unique cuDNN (version 8.2.1 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................8

Table 5. Average speed-up of unique cuDNN (version 8.2.0 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................8

Table 6. Average speed-up of unique cuDNN (version 8.1.1 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................9

Table 7. Average speed-up of unique cuDNN (version 8.1.0 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.................................................................9
Chapter 1. Introduction

**ATTENTION:** These guidelines are applicable to 3D convolution and deconvolution functions starting in NVIDIA® NVIDIA® CUDA® Deep Neural Network library (cuDNN) v7.6.3.

This document provides guidelines for setting the cuDNN library parameters to enhance the performance of 3D convolutions. Specifically, these guidelines are focused on settings such as filter sizes, padding and dilation settings. Additionally, an application-specific use-case, namely, medical imaging, is presented to demonstrate the performance enhancement of 3D convolutions with these recommended settings.

Specifically, these guidelines are applicable to the following functions and their associated data types:

- `cudnnConvolutionForward()`
- `cudnnConvolutionBackwardData()`
- `cudnnConvolutionBackwardFilter()`

For more information, refer to the *NVIDIA cuDNN Developer Guide* and the *NVIDIA cuDNN API Reference*. 
Chapter 2. Best Practices For Medical Imaging

To optimize your performance in your model, ensure you meet the following general guidelines:

**Layout**

The layout is in NCHW format.

**Filter size**

The filter size is $T \times 1 \times 1$, $T \times 2 \times 2$, $T \times 3 \times 3$, $T \times 5 \times 5$, where $T$ is a positive integer. There are additional limits for the value of $T$ in $\text{wgrad}$ and strided $\text{dgrad}$.

**Stride**

Arbitrary for forward and backward filter; $\text{dgrad/deconv}$: $1 \times 1 \times 1$ or $2 \times 2 \times 2$ with $2 \times 2 \times 2$ filter.

**Dilation**

The dilation is $1 \times 1 \times 1$.

**Platform**

The platform is NVIDIA Volta™, NVIDIA Turing™, and NVIDIA Ampere Architecture with input/output channels divisible by 8.

**Batch/image size**

cuDNN will fallback to non-Tensor Core kernel if it determines that the workspace required is larger than 256MB of GPU memory. The workspace required depends on many factors. For the Tensor Core kernels, the workspace size generally scales linearly with output tensor size. Therefore, this can be mitigated by using smaller image sizes or mini-batch sizes.

## 2.1. Recommended Settings In cuDNN While Performing 3D Convolutions

The following tables show the specific improvements that were made in each release.

### 2.1.1. cuDNN 8.x.x Recommended Settings

Recommended settings while performing 3D convolutions for cuDNN 8.x.x.
2.1.2. **cuDNN 7.6.x Recommended Settings**

Recommended settings while performing 3D convolutions for cuDNN 7.6.x.

<table>
<thead>
<tr>
<th></th>
<th>7.6.5</th>
<th>7.6.4</th>
<th>7.6.2</th>
<th>7.6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>NVIDIA Turing</td>
<td>NVIDIA Turing</td>
<td>NVIDIA Volta</td>
<td></td>
</tr>
<tr>
<td>Convolutions (3D or 2D)</td>
<td>3D and 2D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convolutions or deconvolutions (fprop, dgrad, or wgrad)</td>
<td>fprop</td>
<td></td>
<td>fprop</td>
<td>fprop</td>
</tr>
<tr>
<td>Grouped convolution</td>
<td>No</td>
<td></td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Group size</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data layout format</td>
<td>NHWC/NCHW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input/output precision (FP16, FP32, INT8, or FP64)</td>
<td>INT8</td>
<td>FP16 and FP32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accumulator (compute) precision (FP16, FP32, INT8, or FP64)</td>
<td>INT32</td>
<td>FP32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Filter (kernel) sizes</td>
<td>No limitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Padding</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image sizes</td>
<td>2 GB limitation for a tensor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of channels</td>
<td>C 0 mod 16</td>
<td>0 mod 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>K 0 mod 16</td>
<td>0 mod 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convolution mode</td>
<td>Cross-correlation and convolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strides</td>
<td>No limitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilation</td>
<td>No limitation</td>
<td></td>
<td>No limitation</td>
<td></td>
</tr>
<tr>
<td>Data pointer alignment</td>
<td>All data pointers are 16-bytes aligned</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. NHWC/NCHW corresponds to NDHWC/NCDHW in 3D convolution.  
<table>
<thead>
<tr>
<th></th>
<th>7.6.5</th>
<th>7.6.4</th>
<th>7.6.2</th>
<th>7.6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>dgrad</td>
<td>dgrad</td>
<td>dgrad</td>
<td>wgrad</td>
</tr>
<tr>
<td>Grouped convolution</td>
<td>Yes or No</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Group size</td>
<td>C_per_group == K_per_group == (4, 8, 16, 32)</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data layout format [NHWC/NCHW]&lt;sup&gt;3&lt;/sup&gt;</td>
<td>NCDHW</td>
<td>NCDHW&lt;sup&gt;4&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input/output precision [FP16, FP32, or FP64]</td>
<td>FP16</td>
<td>FP16 or FP32</td>
<td>FP16&lt;sup&gt;5&lt;/sup&gt; or FP32&lt;sup&gt;6&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Accumulator (compute) precision [FP16, FP32, or FP64]</td>
<td>FP32</td>
<td>Better to be the same with input/output precision.</td>
<td>FP32</td>
<td></td>
</tr>
<tr>
<td>Filter (kernel) sizes</td>
<td>2x2x2</td>
<td>1x1x1</td>
<td>2x2x2</td>
<td>2x2x2</td>
</tr>
<tr>
<td></td>
<td>T&lt;sup&gt;7&lt;/sup&gt;x1x1</td>
<td>3x3x3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tx2x2</td>
<td>5x5x5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tx3x3</td>
<td>Tx1x1</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tx5x5</td>
<td>Tx2x2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Padding</td>
<td>No limitation</td>
<td>Filter // 2&lt;sup&gt;8&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image sizes</td>
<td>256 MB WS limit</td>
<td>No limitation</td>
<td>256 MB WS limit</td>
<td></td>
</tr>
<tr>
<td>Number of channels</td>
<td>C</td>
<td>Arbitrary</td>
<td>0 mod 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>Arbitrary</td>
<td>0 mod 8</td>
<td></td>
</tr>
<tr>
<td>Convolution mode</td>
<td>Cross-correlation for dgrad; otherwise, both modes</td>
<td>No limitation</td>
<td>Cross-correlation</td>
<td></td>
</tr>
</tbody>
</table>

<sup>3</sup> NHWC/NCHW corresponds to NCHC/NCDEW in 3D convolution.
<sup>4</sup> With NCHW <> NHWC format transformation.
<sup>5</sup> FP16: CUDNN_TENSOROP_MATH
<sup>6</sup> FP32: CUDNN_TENSOROP_MATH_ALLOW_CONVERSION
<sup>7</sup> An arbitrary positive value.
<sup>8</sup> padding = filter // 2
<table>
<thead>
<tr>
<th></th>
<th>7.6.5</th>
<th>7.6.4</th>
<th>7.6.2</th>
<th>7.6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strides</td>
<td>1x1x1 and 2x2x2 strides for $d_{\text{grad}}$</td>
<td>2x2x2 Arbitrary stride</td>
<td>1x1x1</td>
<td></td>
</tr>
<tr>
<td>Dilation</td>
<td></td>
<td></td>
<td></td>
<td>1x1x1</td>
</tr>
</tbody>
</table>
Chapter 3. Medical Imaging Performance

The following table shows the average speed-up of unique cuDNN 3D convolution calls for each network on V100 and A100 GPUs that satisfies the conditions in Best Practices For Medical Imaging. The end-to-end training performance will depend on a number of factors, such as framework overhead, kernel run time, and model architecture type.

3.1. Average Speedup Of Unique cuDNN 3D Convolutions API Calls

3.1.1. cuDNN 8.x.x Average Speedup

cuDNN version 8.3.0 compared to 7.6.5

Table 1. Average speed-up of unique cuDNN (version 8.3.0 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.3.0 vs V100 7.6.5</th>
<th>V100 8.3.0 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net [3D-Image segmentation]</td>
<td>2</td>
<td>2.53x</td>
<td>8.0x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.8x</td>
<td>6.5x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4.6x</td>
<td>7.7x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>6.8x</td>
<td>5.9x</td>
</tr>
<tr>
<td>3D-UNet [3D-Image Segmentation]</td>
<td>2</td>
<td>8.5x</td>
<td>7.7x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>13.2x</td>
<td>6.8x</td>
</tr>
</tbody>
</table>
cuDNN version 8.2.4 compared to 7.6.5

Table 2. Average speed-up of unique cuDNN (version 8.2.4 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.2.4 vs V100 7.6.5</th>
<th>V100 8.2.4 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net [3D-Image segmentation]</td>
<td>2</td>
<td>2.4x</td>
<td>7.4x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.6x</td>
<td>6.3x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4.4x</td>
<td>7.5x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>6.5x</td>
<td>5.7x</td>
</tr>
<tr>
<td>3D-UNet [3D-Image Segmentation]</td>
<td>2</td>
<td>8.0x</td>
<td>7.1x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12.6x</td>
<td>6.3x</td>
</tr>
</tbody>
</table>

cuDNN version 8.2.2 compared to 7.6.5

Table 3. Average speed-up of unique cuDNN (version 8.2.2 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.2.2 vs V100 7.6.5</th>
<th>V100 8.2.2 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net [3D-Image segmentation]</td>
<td>2</td>
<td>2.4x</td>
<td>7.5x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.6x</td>
<td>6.3x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4.4x</td>
<td>7.5x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>6.5x</td>
<td>5.7x</td>
</tr>
<tr>
<td>3D-UNet [3D-Image Segmentation]</td>
<td>2</td>
<td>8.0x</td>
<td>7.1x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12.6x</td>
<td>6.3x</td>
</tr>
</tbody>
</table>
cuDNN version 8.2.1 compared to 7.6.5

Table 4. Average speed-up of unique cuDNN (version 8.2.1 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.2.1 vs V100 7.6.5</th>
<th>V100 8.2.1 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net (3D-Image segmentation)</td>
<td>2</td>
<td>2.5x</td>
<td>7.7x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.7x</td>
<td>6.4x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4.5x</td>
<td>7.5x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>6.5x</td>
<td>5.7x</td>
</tr>
<tr>
<td>3D-UNet (3D-Image Segmentation)</td>
<td>2</td>
<td>8.3x</td>
<td>7.3x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>12.7x</td>
<td>6.4x</td>
</tr>
</tbody>
</table>

cuDNN version 8.2.0 compared to 7.6.5

Table 5. Average speed-up of unique cuDNN (version 8.2.0 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.2.0 vs V100 7.6.5</th>
<th>V100 8.2.0 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net (3D-Image segmentation)</td>
<td>2</td>
<td>2.3x</td>
<td>7.3x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.4x</td>
<td>5.9x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>4.1x</td>
<td>6.8x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>5.8x</td>
<td>5.1x</td>
</tr>
<tr>
<td>3D-UNet (3D-Image Segmentation)</td>
<td>2</td>
<td>6.8x</td>
<td>5.9x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>10.5x</td>
<td>2.6x</td>
</tr>
</tbody>
</table>
cuDNN version 8.1.1 compared to 7.6.5

Table 6. Average speed-up of unique cuDNN (version 8.1.1 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.1.1 vs V100 7.6.5</th>
<th>V100 8.1.1 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net (3D-Image segmentation)</td>
<td>2</td>
<td>2.3x</td>
<td>6.8x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.2x</td>
<td>5.1x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>3.8x</td>
<td>5.9x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>5.4x</td>
<td>4.4x</td>
</tr>
<tr>
<td>3D-UNet (3D-Image Segmentation)</td>
<td>2</td>
<td>7.2x</td>
<td>6.3x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11x</td>
<td>2.6x</td>
</tr>
</tbody>
</table>

cuDNN version 8.1.0 compared to 7.6.5

Table 7. Average speed-up of unique cuDNN (version 8.1.0 compared to 7.6.5) 3D convolution API calls on V100 and A100 for both FP16 and FP32.

<table>
<thead>
<tr>
<th>Model</th>
<th>Batchsize</th>
<th>A100 8.1.0 vs V100 7.6.5</th>
<th>V100 8.1.0 vs V100 7.6.5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FP16</td>
<td>FP32</td>
</tr>
<tr>
<td>V-Net (3D-Image segmentation)</td>
<td>2</td>
<td>2.4x</td>
<td>7.3x</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.4x</td>
<td>5.3x</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>3.9x</td>
<td>6x</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>5.5x</td>
<td>4.4x</td>
</tr>
<tr>
<td>3D-UNet (3D-Image Segmentation)</td>
<td>2</td>
<td>7.3x</td>
<td>6.4x</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>11.2x</td>
<td>2.6x</td>
</tr>
</tbody>
</table>
Chapter 4. Medical Imaging
Limitations

Your application will be functional but slow if the model has:

- Channel counts lower than 32 (gets worse the lower it is)
- Data gradients for convolutions with stride

If the above is in the network, use `cudnnFind` to get the best option.
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