cuDNN Developer Guide

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Chapter 1. Overview

NVIDIA® CUDA® Deep Neural Network library™ (cuDNN) is a GPU-accelerated library of primitives for deep neural networks. It provides highly tuned implementations of routines arising frequently in DNN applications:

- Convolution forward and backward, including cross-correlation
- Pooling forward and backward
- Softmax forward and backward
- Neuron activations forward and backward:
  - Rectified linear (ReLU)
  - Sigmoid
  - Hyperbolic tangent (TANH)
- Tensor transformation functions
- LRN, LCN and batch normalization forward and backward

cuDNN convolution routines aim for a performance that is competitive with the fastest GEMM (matrix multiply)-based implementations of such routines while using significantly less memory.

cuDNN features include customizable data layouts, supporting flexible dimension ordering, striding, and subregions for the 4D tensors used as inputs and outputs to all of its routines. This flexibility allows easy integration into any neural network implementation and avoids the input/output transposition steps sometimes necessary with GEMM-based convolutions.

cuDNN offers a context-based API that allows for easy multithreading and (optional) interoperability with NVIDIA® CUDA® streams.

Chapter 2. Programming Model

The cuDNN library exposes a Host API but assumes that for operations using the GPU, the necessary data is directly accessible from the device.

An application using cuDNN must initialize a handle to the library context by calling cudnnCreate(). This handle is explicitly passed to every subsequent library function that operates on GPU data. Once the application finishes using cuDNN, it can release the resources associated with the library handle using cudnnDestroy(). This approach allows the user to explicitly control the library's functioning when using multiple host threads, GPUs and CUDA Streams.

For example, an application can use cudaSetDevice to associate different devices with different host threads, and in each of those host threads, use a unique cuDNN handle that directs the library calls to the device associated with it. Thus the cuDNN library calls made with different handles will automatically run on different devices.

The device associated with a particular cuDNN context is assumed to remain unchanged between the corresponding `cudnnCreate()` and `cudnnDestroy()` calls. In order for the cuDNN library to use a different device within the same host thread, the application must set the new device to be used by calling `cudaSetDevice()` and then create another cuDNN context, which will be associated with the new device, by calling `cudnnCreate()`.

cuDNN API Compatibility

Beginning in cuDNN 7, the binary compatibility of a patch and minor releases is maintained as follows:

- Any patch release x.y.z is forward or backward-compatible with applications built against another cuDNN patch release x.y.w (meaning, of the same major and minor version number, but having w!=z).
- cuDNN minor releases beginning with cuDNN 7 are binary backward-compatible with applications built against the same or earlier patch release (meaning, an application built against cuDNN 7.x is binary compatible with cuDNN library 7.y, where y>=x).
- Applications compiled with a cuDNN version 7.y are not guaranteed to work with 7.x release when y > x.

Chapter 3. Convolution Formulas

This section describes the various convolution formulas implemented in convolution functions.

The convolution terms described in the table below apply to all the convolution formulas that follow.

Table 1. Convolution terms

Term	Description
x	Input (image) Tensor
w	Weight Tensor
y	Output Tensor
n	Current Batch Size
c	Current Input Channel
C	Total Input Channels
H	Input Image Height
W	Input Image Width
k	Current Output Channel
K	Total Output Channels
p	Current Output Height Position
q	Current Output Width Position
G	Group Count
pad	Padding Value
u	Vertical Subsample Stride (along Height)
v	Horizontal Subsample Stride (along Width)
dil_h	Vertical Dilation (along Height)
dil_w	Horizontal Dilation (along Width)
r	Current Filter Height
R	Total Filter Height
s	Current Filter Width
S	Total Filter Width

Term	Description
C_g	$\frac{C}{G}$
K_g	$\frac{K}{G}$

Normal Convolution (using cross-correlation mode)

$$y_{n,\,k,\,p,\,q} = \sum_{c}^{C} \sum_{r}^{R} \sum_{s}^{S} x_{n,\,c,\,p+r,\,q+s} \times w_{k,c,r,s}$$

Convolution with Padding

$$x_{<0,\,<0} = 0$$

$$x_{>H,\,>W} = 0$$

$$y_{n,\,k,\,p,\,q} = \sum_{c}^{C} \sum_{r}^{R} \sum_{s}^{S} x_{n,\,c,\,p+r-pad,\,q+s-pad} \times w_{k,c,r,s}$$

Convolution with Subsample-Striding

$$y_{n,\,k,\,p,\,q} = \sum_{c}^{C} \sum_{r}^{R} \sum_{s}^{S} x_{n,\,c,\,(p*u)+r,\,(q*v)+s} \times w_{k,c,r,s}$$

Convolution with Dilation

$$y_{n,\,k,\,p,\,q} = \sum_{c}^{C} \sum_{r}^{R} \sum_{s}^{S} x_{n,\,c,\,p+(r*dilh),\,q+(s*dilw)} \times w_{k,c,r,s}$$

Convolution using Convolution Mode

$$y_{n,\,k,\,p,\,q} = \sum_{c}^{C} \sum_{r}^{R} \sum_{s}^{S} x_{n,\,c,\,p+r,\,q+s} \times w_{k,\,c,\,R-r-1,\,S-s-1}$$

Convolution using Grouped Convolution

$$C_g = \frac{C}{G}$$

$$K_g = \frac{K}{G}$$

$$y_{n,\,k,\,p,\,q} = \sum_{c}^{C_g} \sum_{r}^{R} \sum_{s}^{S} x_{n,\,Cg*floor(k/Kg)+c,\,p+r,\,q+s} \times w_{k,c,r,s}$$

Chapter 4. Notation

As of cuDNN version 4, we have adopted a mathematically-inspired notation for layer inputs and outputs using `x,y,dx,dy,b,w` for common layer parameters. This was done to improve readability and ease of understanding of the meaning of the parameters. All layers now follow a uniform convention as below:

During inference

```
y = layerFunction(x, otherParams)
```

During backpropagation

```
(dx, dOtherParams) = layerFunctionGradient(x,y,dy,otherParams)
```

During convolution

For **convolution**, the notation is:

```
y = x*w+b
```

where:

- `w` is the matrix of filter weights
- `x` is the previous layer's data (during inference)
- `y` is the next layer's data
- `b` is the bias and `*` is the convolution operator

In backpropagation routines, the parameters keep their meanings.

The parameters `dx,dy,dw,db` always refer to the gradient of the final network error function with respect to a given parameter. So `dy` in all backpropagation routines always refers to error gradient backpropagated through the network computation graph so far. Similarly, other parameters in more specialized layers, such as, for instance, `dMeans` or `dBnBias` refer to gradients of the loss function with regard to those parameters.

Note: `w` is used in the API for both the width of the `x` tensor and convolution filter matrix. To resolve this ambiguity we use `w` and `filter` notation interchangeably for the convolution filter weight matrix. The meaning is clear from the context since the layer width is always referenced near its height.

Chapter 5. Tensor Descriptor

The cuDNN library describes data holding images, videos and any other data with contents with a generic n-D tensor defined with the following parameters:

- a dimension `nbDims` from 3 to 8
- a data type (32-bit floating-point, 64 bit-floating point, 16-bit floating-point...)
- `dimA` integer array defining the size of each dimension
- `strideA` integer array defining the stride of each dimension (for example, the number of elements to add to reach the next element from the same dimension)

The first dimension of the tensor defines the batch size `n`, and the second dimension defines the number of features maps `c`. This tensor definition allows, for example, to have some dimensions overlapping each other within the same tensor by having the stride of one dimension smaller than the product of the dimension and the stride of the next dimension. In cuDNN, unless specified otherwise, all routines will support tensors with overlapping dimensions for forward-pass input tensors, however, dimensions of the output tensors cannot overlap. Even though this tensor format supports negative strides (which can be useful for data mirroring), cuDNN routines do not support tensors with negative strides unless specified otherwise.

5.1. WXYZ Tensor Descriptor

Tensor descriptor formats are identified using acronyms, with each letter referencing a corresponding dimension. In this document, the usage of this terminology implies:

- all the strides are strictly positive
- the dimensions referenced by the letters are sorted in decreasing order of their respective strides

5.2. 4-D Tensor Descriptor

A 4-D Tensor descriptor is used to define the format for batches of 2D images with 4 letters: `N,C,H,W` for respectively the batch size, the number of feature maps, the height and the width. The letters are sorted in decreasing order of the strides. The commonly used 4-D tensor formats are:

- NCHW
- NHWC
- CHWN

5.3. 5-D Tensor Description

A 5-D Tensor descriptor is used to define the format of the batch of 3D images with 5 letters: N,C,D,H,W for respectively the batch size, the number of feature maps, the depth, the height, and the width. The letters are sorted in decreasing order of the strides. The commonly used 5-D tensor formats are called:

- NCDHW
- NDHWC
- CDHWN

5.4. Fully-packed Tensors

A tensor is defined as XYZ-fully-packed if and only if:

- the number of tensor dimensions is equal to the number of letters preceding the fully-packed suffix.
- the stride of the i-th dimension is equal to the product of the (i+1)-th dimension by the (i +1)-th stride.
- the stride of the last dimension is 1.

5.5. Partially-packed Tensors

The partially XYZ-packed terminology only applies in the context of a tensor format described with a superset of the letters used to define a partially-packed tensor. A WXYZ tensor is defined as XYZ-packed if and only if:

- The strides of all dimensions NOT referenced in the -packed suffix are greater or equal to the product of the next dimension by the next stride.
- The stride of each dimension referenced in the -packed suffix in position i is equal to the product of the (i+1)-st dimension by the (i+1)-st stride.
- If the last tensor's dimension is present in the -packed suffix, its stride is 1.

For example, an NHWC tensor WC-packed means that the c_stride is equal to 1 and w_stride is equal to c_dim x c_stride. In practice, the -packed suffix is usually applied to the minor dimensions of a tensor but can be applied to only the major dimensions; for example, an NCHW tensor that is only N-packed.

5.6. Spatially Packed Tensors

Spatially-packed tensors are defined as partially-packed in spatial dimensions.

For example, a spatially-packed 4D tensor would mean that the tensor is either NCHW HW-packed or CNHW HW-packed.

5.7. Overlapping Tensors

A tensor is defined to be overlapping if iterating over a full range of dimensions produces the same address more than once.

In practice an overlapped tensor will have `stride[i-1] < stride[i]*dim[i]` for some of the `i` from `[1,nbDims]` interval.

Chapter 6. Data Layout Formats

This section describes how cuDNN tensors are arranged in memory. See cudnnTensorFormat_t for enumerated tensor format types.

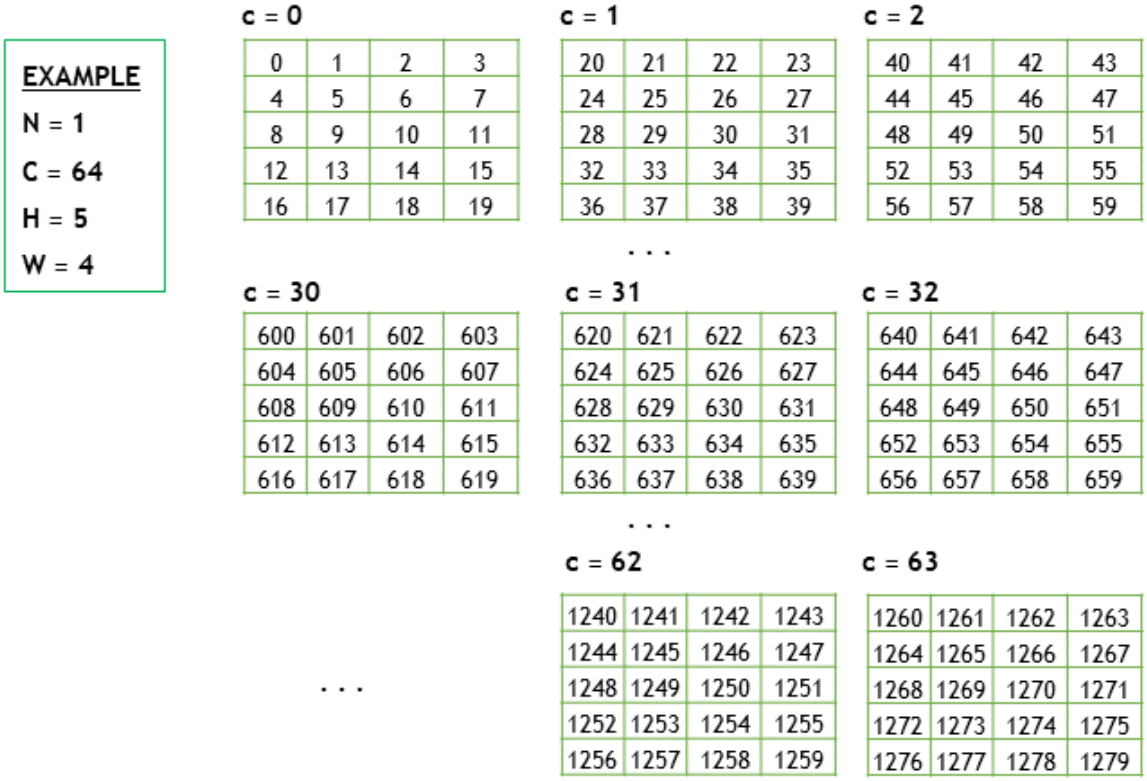
6.1. Example

Consider a batch of images in 4D with the following dimensions:

- **N** is the batch size; 1.
- **C** is the number of feature maps (i.e., number of channels); 64.
- **H** is the image height; 5.
- **W** is the image width; 4.

To keep the example simple, the image pixel elements are expressed as a sequence of integers, 0, 1, 2, 3, and so on. See Figure 1.

Figure 1. Example with N=1, C=64, H=5, W=4.

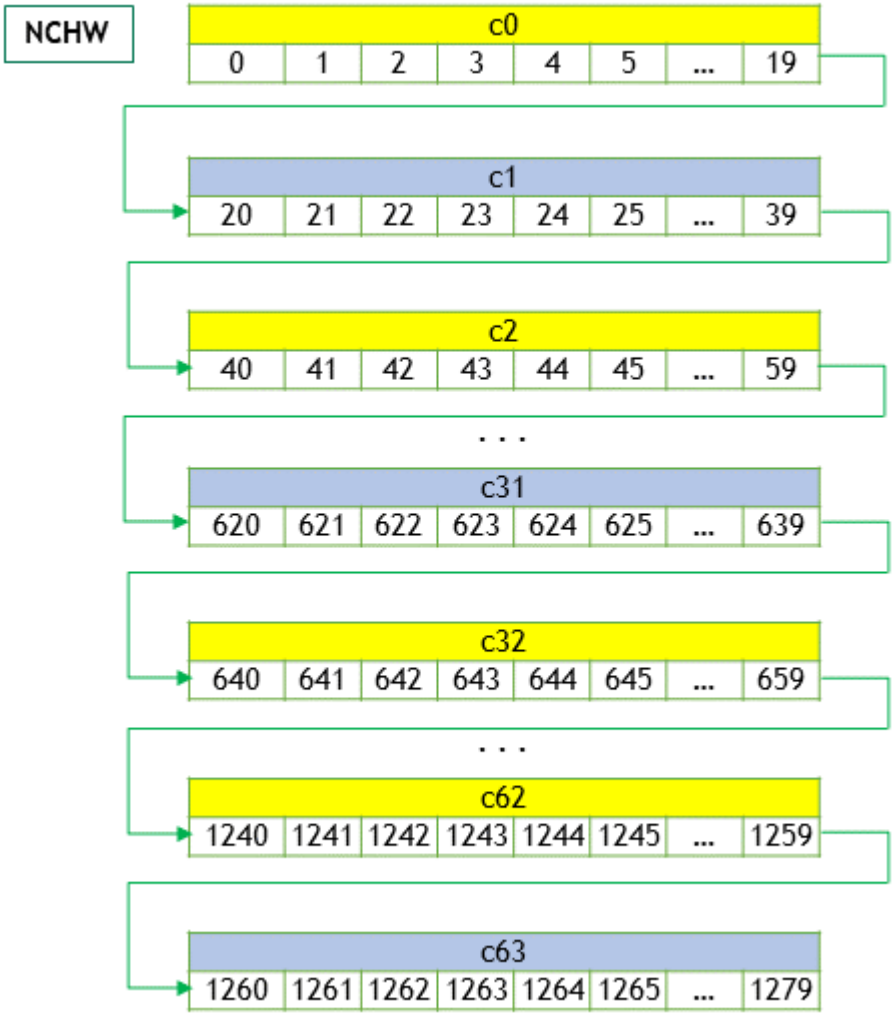


6.2. NCHW Memory Layout

The above 4D Tensor is laid out in the memory in the NCHW format as below:

1. Beginning with the first channel (c=0), the elements are arranged contiguously in row-major order.
2. Continue with second and subsequent channels until the elements of all the channels are laid out. See Figure 2.
3. Proceed to the next batch (if **N** is > 1).

Figure 2. NCHW Memory Layout

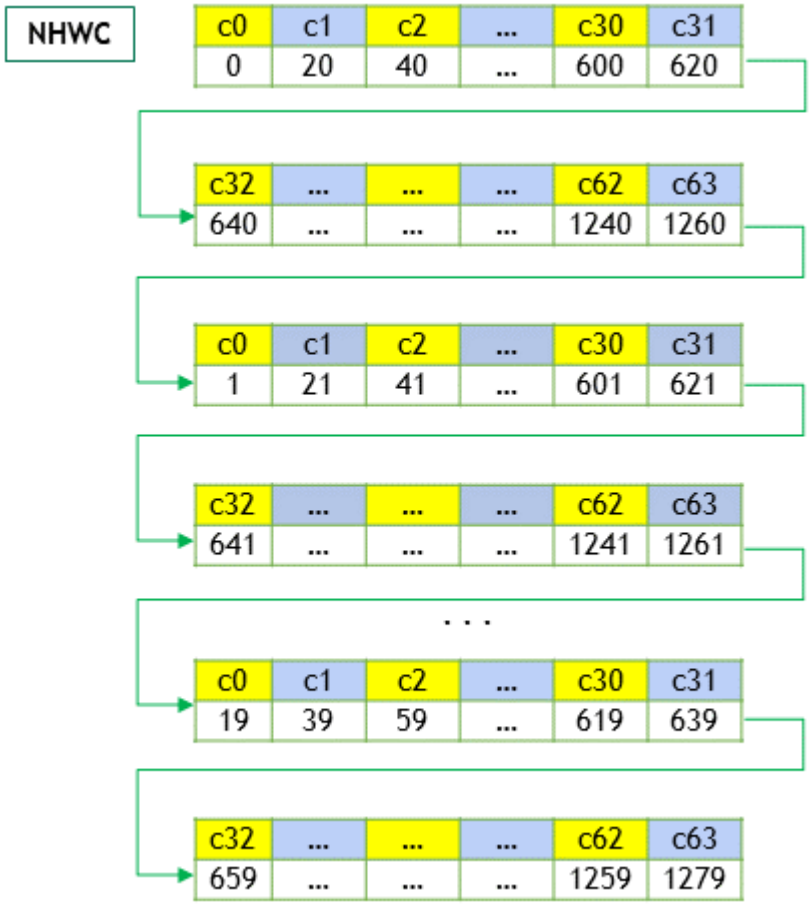


6.3. NHWC Memory Layout

For the NHWC memory layout, the corresponding elements in all the **C** channels are laid out first, as below:

1. Begin with the first element of channel 0, then proceed to the first element of channel 1, and so on, until the first elements of all the **C** channels are laid out.
2. Next, select the second element of channel 0, then proceed to the second element of channel 1, and so on, until the second element of all the channels are laid out.
3. Follow the row-major order of channel 0 and complete all the elements. See Figure 3.
4. Proceed to the next batch (if **N** is > 1).

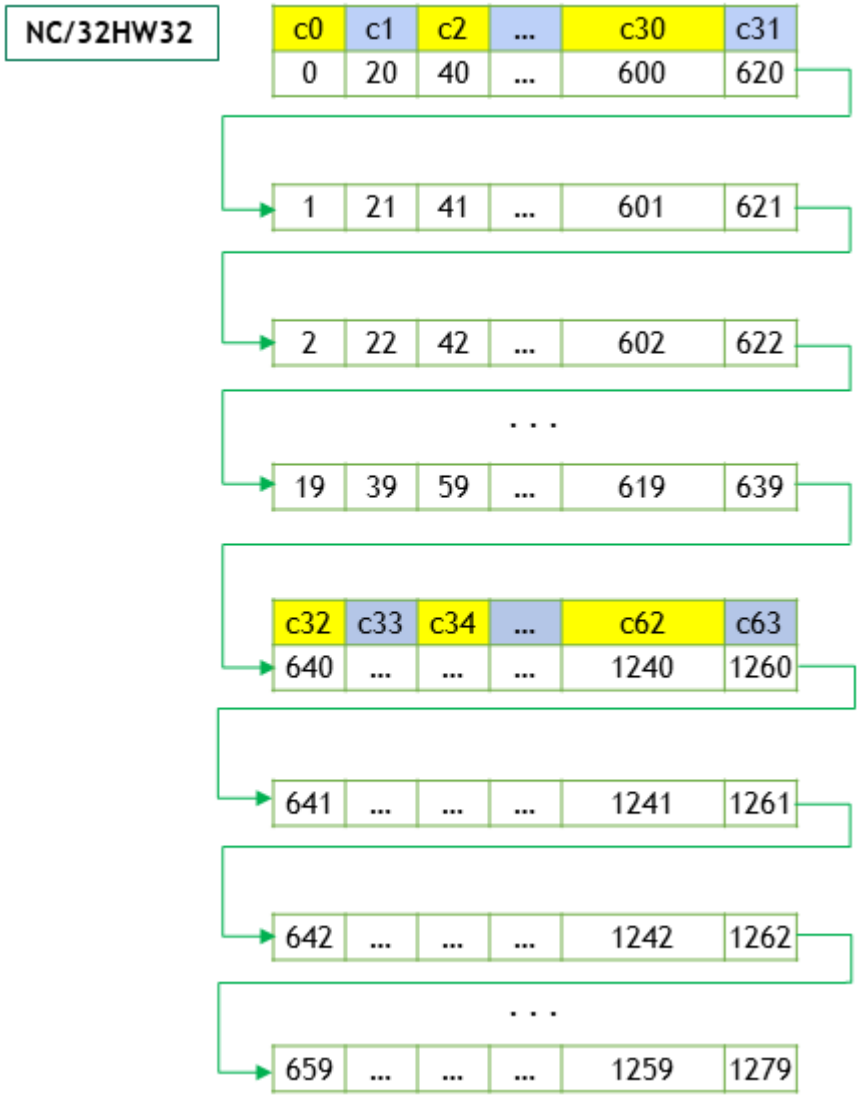
Figure 3. NHWC Memory Layout



6.4. NC/32HW32 Memory Layout

The NC/32HW32 is similar to NHWC, with a key difference. For the NC/32HW32 memory layout, the 64 channels are grouped into two groups of 32 channels each—first group consisting of channels c0 through c31, and the second group consisting of channels c32 through c63. Then each group is laid out using the NHWC format. See Figure 4.

Figure 4. NC/32HW32 Memory Layout



For the generalized NC/xHWx layout format, the following observations apply:

- Only the channel dimension, **C**, is grouped into x channels each.
- When x = 1, each group has only one channel. Hence, the elements of one channel (i.e, one group) are arranged contiguously (in the row-major order), before proceeding to the next group (i.e., next channel). This is the same as NCHW format.
- When x = C, then NC/xHWx is identical to NHWC, i.e., the entire channel depth C is considered as a single group. The case x = C can be thought of as vectorizing the entire C dimension as one big vector, laying out all the Cs, followed by the remaining dimensions, just like NHWC.
- The tensor format CUDNN_TENSOR_NCHW_VECT_C can also be interpreted in the following way: The NCHW INT8x32 format is really N x (C/32) x H x W x 32 (32 Cs for every

W), just as the NCHW INT8x4 format is N x (C/4) x H x W x 4 (4 Cs for every W). Hence the "VECT_C" name - each W is a vector (4 or 32) of Cs.

Chapter 7. Thread Safety

The library is thread-safe and its functions can be called from multiple host threads, as long as threads do not share the same cuDNN handle simultaneously.

Chapter 8. Reproducibility (determinism)

By design, most of cuDNN routines from a given version generate the same bit-wise results across runs when executed on GPUs with the same architecture and the same number of SMs. However, bit-wise reproducibility is not guaranteed across versions, as the implementation of a given routine may change. With the current release, the following routines do not guarantee reproducibility because they use atomic operations:

- `cudnnConvolutionBackwardFilter` when `CUDNN_CONVOLUTION_BWD_FILTER_ALGO_0` or `CUDNN_CONVOLUTION_BWD_FILTER_ALGO_3` is used
- `cudnnConvolutionBackwardData` when `CUDNN_CONVOLUTION_BWD_DATA_ALGO_0` is used
- `cudnnPoolingBackward` when `CUDNN_POOLING_MAX` is used
- `cudnnSpatialTfSamplerBackward`
- `cudnnCTCLoss` and `cudnnCTCLoss_v8` when `CUDNN_CTC_LOSS_ALGO_NON_DETERMINSTIC` is used

Chapter 9. Scaling Parameters

Many cuDNN routines like cudnnConvolutionForward() accept pointers in host memory to scaling factors `alpha` and `beta`. These scaling factors are used to blend the computed values with the prior values in the destination tensor as follows (see Figure 5):

```
dstValue = alpha*computedValue + beta*priorDstValue
```

Note: The `dstValue` is written to after being read.

Figure 5. Scaling Parameters for Convolution

When `beta` is zero, the output is not read and may contain uninitialized data (including NaN).

These parameters are passed using a host memory pointer. The storage data types for `alpha` and `beta` are:

- `float` for HALF and FLOAT tensors, and
- `double` for DOUBLE tensors.

Note: For improved performance use `beta` = 0.0. Use a non-zero value for beta only when you need to blend the current output tensor values with the prior values of the output tensor.

Type Conversion

When the data input `x`, the filter input `w` and the output `y` are all in INT8 data type, the function cudnnConvolutionBiasActivationForward() will perform the type conversion as shown in Figure 6:

Note: Accumulators are 32-bit integers that wrap on overflow.

Figure 6. INT8 for cudnnConvolutionBiasActivationForward

Chapter 10. Tensor Core Operations

The cuDNN v7 library introduced the acceleration of compute-intensive routines using Tensor Core hardware on supported GPU SM versions. Tensor Core operations are supported beginning with the Volta GPU.

10.1. Basics

Tensor Core operations perform parallel floating-point accumulation of multiple floating-point product terms. Setting the math mode to `CUDNN_TENSOR_OP_MATH` via the cudnnMathType_t enumerator indicates that the library will use Tensor Core operations. This enumerator specifies the available options to enable the Tensor Core and should be applied on a per-routine basis.

The default math mode is `CUDNN_DEFAULT_MATH`, which indicates that the Tensor Core operations will be avoided by the library. Because the `CUDNN_TENSOR_OP_MATH` mode uses the Tensor Cores, it is possible that these two modes generate slightly different numerical results due to different sequencing of the floating-point operations.

For example, the result of multiplying two matrices using Tensor Core operations is very close, but not always identical, to the result achieved using a sequence of scalar floating-point operations. For this reason, the cuDNN library requires an explicit user opt-in before enabling the use of Tensor Core operations.

However, experiments with training common deep learning models show negligible differences between using Tensor Core operations and scalar floating point paths, as measured by both the final network accuracy and the iteration count to convergence. Consequently, the cuDNN library treats both modes of operation as functionally indistinguishable and allows for the scalar paths to serve as legitimate fallbacks for cases in which the use of Tensor Core operations is unsuitable.

Kernels using Tensor Core operations are available for both convolutions and RNNs.

See also Training with Mixed Precision.

10.2. Convolution Functions

10.2.1. Prerequisites

For the supported GPUs, the Tensor Core operations will be triggered for convolution functions only when cudnnSetConvolutionMathType() is called on the appropriate convolution descriptor by setting the `mathType` to `CUDNN_TENSOR_OP_MATH` or `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION`.

10.2.2. Supported Algorithms

When the prerequisite is met, the below convolution functions can be run as Tensor Core operations:

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

See the table below for supported algorithms:

Supported Convolution Function	Supported Algos
`cudnnConvolutionForward`	▶ `CUDNN_CONVOLUTION_FWD_ALGO_IMPLICIT_PRECOMP_GEMM` ▶ `CUDNN_CONVOLUTION_FWD_ALGO_WINOGRAD_NONFUSED`
`cudnnConvolutionBackwardData`	▶ `CUDNN_CONVOLUTION_BWD_DATA_ALGO_1` ▶ `CUDNN_CONVOLUTION_BWD_DATA_ALGO_WINOGRAD_NONFUSED`
`cudnnConvolutionBackwardFilter`	▶ `CUDNN_CONVOLUTION_BWD_FILTER_ALGO_1` ▶ `CUDNN_CONVOLUTION_BWD_FILTER_ALGO_WINOGRAD_NONFUSED`

10.2.3. Data And Filter Formats

The cuDNN library may use padding, folding, and NCHW-to-NHWC transformations to call the Tensor Core operations. See Tensor Transformations.

For algorithms other than `*_ALGO_WINOGRAD_NONFUSED`, when the following requirements are met, the cuDNN library will trigger the Tensor Core operations:

- Input, filter, and output descriptors (`xDesc`, `yDesc`, `wDesc`, `dxDesc`, `dyDesc` and `dwDesc` as applicable) are of the `dataType = CUDNN_DATA_HALF` (i.e., FP16). For FP32 `dataType` see FP32-to-FP16 Conversion.
- The number of input and output feature maps (i.e., channel dimension `C`) is a multiple of 8. When the channel dimension is not a multiple of 8, see Padding.
- The filter is of type `CUDNN_TENSOR_NCHW` or `CUDNN_TENSOR_NHWC`.
- If using a filter of type `CUDNN_TENSOR_NHWC`, then the input, filter, and output data pointers (`X`, `Y`, `W`, `dX`, `dY`, and `dW` as applicable) are aligned to 128-bit boundaries.

10.3. RNN Functions

10.3.1. Prerequisites

Tensor core operations will be triggered for these RNN functions only when cudnnSetRNNMatrixMathType() is called on the appropriate RNN descriptor setting `mathType` to `CUDNN_TENSOR_OP_MATH` or `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION`.

10.3.2. Supported Algorithms

When the above prerequisite is met, the RNN functions below can be run as Tensor Core operations:

- cudnnRNNForwardInference()
- cudnnRNNForwardTraining()
- cudnnRNNBackwardData()
- cudnnRNNBackwardWeights()
- cudnnRNNForwardInferenceEx()
- cudnnRNNForwardTrainingEx()
- cudnnRNNBackwardDataEx()
- cudnnRNNBackwardWeightsEx()

See the table below for the supported algorithms:

RNN Function	Support Algos
All RNN functions that support Tensor Core operations.	▶ `CUDNN_RNN_ALGO_STANDARD` ▶ `CUDNN_RNN_ALGO_PERSIST_STATIC`

10.3.3. Data And Filter Formats

When the following requirements are met, then the cuDNN library will trigger the Tensor Core operations:

- For `algo = CUDNN_RNN_ALGO_STANDARD`:
  - The hidden state size, input size, and the batch size is a multiple of 8.
  - All user-provided tensors, workspace, and reserve space are aligned to 128-bit boundaries.
  - For FP16 input/output, the `CUDNN_TENSOR_OP_MATH` or `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` is selected.
  - For FP32 input/output, `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` is selected.

- For `algo = CUDNN_RNN_ALGO_PERSIST_STATIC`:
  - The hidden state size and the input size is a multiple of 32.
  - The batch size is a multiple of 8.
  - If the batch size exceeds 96 (for forward training or inference) or 32 (for backward data), then the batch size constraints may be stricter, and large power-of-two batch sizes may be needed.
  - All user-provided tensors, workspace, and reserve space are aligned to 128-bit boundaries.
  - For FP16 input/output, `CUDNN_TENSOR_OP_MATH` or `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` is selected.
  - For FP32 input/output, `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` is selected.

See also Features Of RNN Functions.

10.4. Tensor Transformations

A few functions in the cuDNN library will perform transformations such as folding, padding, and NCHW-to-NHWC conversion while performing the actual function operation. See below.

10.4.1. FP16 Data

Tensor Cores operate on FP16 input data with FP32 accumulation. The FP16 multiply leads to a full-precision result that is accumulated in FP32 operations with the other products in a given dot product for a matrix with `m x n x k` dimensions. See Figure 7.

Figure 7. Tensor Operation with FP16 Inputs

10.4.2. FP32-to-FP16 Conversion

The cuDNN API allows the user to specify that FP32 input data may be copied and converted to FP16 data internally to use Tensor Core operations for potentially improved performance. This can be achieved by selecting `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` enum for cudnnMathType_t. In this mode, the FP32 tensors are internally down-converted to FP16, the Tensor Op math is performed, and finally up-converted to FP32 as outputs. See Figure 8.

Figure 8. Tensor Operation with FP32 Inputs

For Convolutions

For convolutions, the FP32-to-FP16 conversion can be achieved by passing the `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` enum value to the cudnnSetConvolutionMathType() call.

```
// Set the math type to allow cuDNN to use Tensor Cores:
```

```
checkCudnnErr(cudnnSetConvolutionMathType(cudnnConvDesc,
 CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION));
```

For RNNs

For RNNs, the FP32-to-FP16 conversion can be achieved by passing the `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` enum value to the cudnnSetRNNMatrixMathType() call to allow FP32 data to be converted for use in RNNs.

```
// Set the math type to allow cuDNN to use Tensor Cores:
checkCudnnErr(cudnnSetRNNMatrixMathType(cudnnRnnDesc,
 CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION));
```

10.4.3. Padding

For packed NCHW data, when the channel dimension is not a multiple of 8, then the cuDNN library will pad the tensors as needed to enable Tensor Core operations. This padding is automatic for packed NCHW data in both the `CUDNN_TENSOR_OP_MATH` and the `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` cases.

The padding occurs with a negligible loss of performance. Hence, the NCHW tensor dimensions such as below are allowed:

```
// Set NCHW Tensor dimensions, not necessarily as multiples of eight (only the input
 tensor is shown here):
int dimA[] = {1, 7, 32, 32};
int strideA[] = {7168, 1024, 32, 1};
```

10.4.4. Folding

In the folding operation, the cuDNN library implicitly performs the formatting of input tensors and saves the input tensors in an internal workspace. This can lead to an acceleration of the call to Tensor Cores.

Folding enables the input tensors to be transformed into a format that the Tensor Cores support (i.e., no strides).

10.4.5. Conversion Between NCHW And NHWC

Tensor Cores require that the tensors be in the NHWC data layout. Conversion between NCHW and NHWC is performed when the user requests Tensor Op math. However, as stated in Basics, a request to use Tensor Cores is just that, a request and Tensor Cores may not be used in some cases. The cuDNN library converts between NCHW and NHWC if and only if Tensor Cores are requested and are actually used.

If your input (and output) are NCHW, then expect a layout change.

Non-Tensor Op convolutions will not perform conversions between NCHW and NHWC.

In very rare and difficult-to-qualify cases that are a complex function of padding and filter sizes, it is possible that Tensor Ops is not enabled. In such cases, users should pre-pad.

10.5. Guidelines For A Deep Learning Compiler

For a deep learning compiler, the following are the key guidelines:

- Make sure that the convolution operation is eligible for Tensor Cores by avoiding any combinations of large padding and large filters.
- Transform the inputs and filters to NHWC, pre-pad channel and batch size to be a multiple of 8.
- Make sure that all user-provided tensors, workspace, and reserve space are aligned to 128-bit boundaries.

Chapter 11. GPU And Driver Requirements

For the latest compatibility software versions of the OS, CUDA, the CUDA driver, and the NVIDIA hardware, see the cuDNN Support Matrix.

Chapter 12. Backward Compatibility And Deprecation Policy

cuDNN version 8 introduces a new API deprecation policy to enable a faster pace of innovation.

The old deprecation policy required three major library releases to complete an API update. During this process, the original function name was first assigned to the legacy API, and then to the revised API, depending on the library version. The user wishing to migrate to the new API version had to update his or her code twice. In the first update, the original call `foo()` had to be changed to `foo_vN()`, where `N` is the new major cuDNN version. After the next major cuDNN release, the `foo_vN()` function had to be renamed back as `foo()`. Clearly, the above process could be difficult for code maintenance, especially when many functions are upgraded.

A streamlined, two-step, deprecation policy will be used for all API changes starting with cuDNN version 8. Let us explain the process using two subsequent, major cuDNN releases, version 8 and 9:

Table 2. Two-step, deprecation policy

cuDNN version	Explanation
Major release 8	The updated API is introduced as `foo_v8()`. The deprecated API `foo()` is kept unchanged to maintain backward compatibility until the next major release.
Major release 9	The deprecated API `foo()` is permanently removed and its name is not reused. The `foo_v8()` function supersedes the retired call `foo()`.

If the existing API needs to be updated, a new function flavor is introduced with the `_v` tag followed by the current, major cuDNN version. In the next major release, the deprecated function is removed, and its name is never reused. A brand-new API is first introduced without the `_v` tag.

The revised deprecation scheme allows us to retire the legacy API in just one major release. Similarly to the previous API deprecation policy, the user is able to compile the legacy code without any changes using the next major release of the cuDNN library. The backward compatibility ends when another major cuDNN release is introduced.

The updated function name embeds the information in which the cuDNN version of the API call was modified. As a result, the API changes will be easier to track and document.

The new deprecation policy is applied also to pending API changes from previous cuDNN releases. For example, according to the old deprecation policy, `cudnnSetRNNDescriptor_v6()` should be removed in cuDNN version 8 and the upgraded call `cudnnSetRNNDescriptor()` with the same arguments and behavior should be kept. Instead, the new deprecation policy is applied to this case and the tagged function is kept.

Prototypes of deprecated functions will be prepended in cuDNN version 8 headers using the `CUDNN_DEPRECATED` macro. When the `–DCUDNN_WARN_DEPRECATED` switch is passed to the compiler, any deprecated function call in the user's code will emit a compiler warning, for example:

```
warning: ‘cudnnStatus_t cudnnSetRNNMatrixMathType(cudnnRNNDescriptor_t, cudnnMathType_t)’ is
 deprecated [-Wdeprecated-declarations]
```

Or

```
warning C4996: 'cudnnSetRNNMatrixMathType': was declared deprecated
```

The above warnings are disabled by default to avoid potential build breaks in software setups where compiler warnings are treated as errors.

Note that the simple swapping of older cuDNN version 7 shared library files will not work with the cuDNN version 8 release. The user source code needs to be recompiled from scratch with the cuDNN version 8 headers and linked with the version 8 libraries.

Chapter 13. Grouped Convolutions

cuDNN supports grouped convolutions by setting `groupCount` > 1 for the convolution descriptor `convDesc`, using `cudnnSetConvolutionGroupCount()`.

Note: By default, the convolution descriptor `convDesc` is set to `groupCount` of 1.

Basic Idea

Conceptually, in grouped convolutions, the input channels and the filter channels are split into `groupCount` number of independent groups, with each group having a reduced number of channels. The convolution operation is then performed separately on these input and filter groups.

For example, consider the following: if the number of input channels is 4, and the number of filter channels of 12. For a normal, ungrouped convolution, the number of computation operations performed are 12*4.

If the `groupCount` is set to 2, then there are now two input channel groups of two input channels each, and two filter channel groups of six filter channels each.

As a result, each grouped convolution will now perform 2*6 computation operations, and two such grouped convolutions are performed. Hence the computation savings are 2x: (12*4)/(2*(2*6))

cuDNN Grouped Convolution

- When using `groupCount` for grouped convolutions, you must still define all tensor descriptors so that they describe the size of the entire convolution, instead of specifying the sizes per group.
- Grouped convolutions are supported for all formats that are currently supported by the functions `cudnnConvolutionForward()`, `cudnnConvolutionBackwardData()` and `cudnnConvolutionBackwardFilter()`.
- The tensor stridings that are set for `groupCount` of 1 are also valid for any group count.
- By default, the convolution descriptor `convDesc` is set to `groupCount` of 1.

Note: See Convolution Formulas for the math behind the cuDNN Grouped Convolution.

Example

Below is an example showing the dimensions and strides for grouped convolutions for NCHW format, for 2D convolution.

Note: The symbols "*" and "/" are used to indicate multiplication and division.

`xDesc or dxDesc:`

- **Dimensions**: `[batch_size, input_channel, x_height, x_width]`
- **Strides**: `[input_channels*x_height*x_width, x_height*x_width, x_width, 1]`

`wDesc or dwDesc:`

- **Dimensions**: `[output_channels, input_channels/groupCount, w_height, w_width]`
- **Format**: `NCHW`

`convDesc:`

- **Group Count**: `groupCount`

`yDesc or dyDesc:`

- **Dimensions**: `[batch_size, output_channels, y_height, y_width]`
- **Strides**: `[output_channels*y_height*y_width, y_height*y_width, y_width, 1]`

Chapter 14. API Logging

cuDNN API logging is a tool that records all input parameters passed into every cuDNN API function call. This functionality is disabled by default, and can be enabled through methods described in this section.

The log output contains variable names, data types, parameter values, device pointers, process ID, thread ID, cuDNN handle, CUDA stream ID, and metadata such as time of the function call in microseconds.

When logging is enabled, the log output will be handled by the built-in default callback function. The user may also write their own callback function, and use the cudnnSetCallback() to pass in the function pointer of their own callback function. The following is a sample output of the API log.

```
Function cudnnSetActivationDescriptor() called:
mode: type=cudnnActivationMode_t; val=CUDNN_ACTIVATION_RELU (1);
reluNanOpt: type=cudnnNanPropagation_t; val=CUDNN_NOT_PROPAGATE_NAN (0);
coef: type=double; val=1000.000000;
Time: 2017-11-21T14:14:21.366171 (0d+0h+1m+5s since start)
Process: 21264, Thread: 21264, cudnn_handle: NULL, cudnn_stream: NULL.
```

There are two methods to enable API logging.

Method 1: Using Environment Variables

To enable API logging using environment variables, follow these steps:

- Set the environment variable `CUDNN_LOGINFO_DBG` to "1", and
- Set the environment variable `CUDNN_LOGDEST_DBG` to one of the following:
  - `stdout`, `stderr`, or a user-desired file path, for example, `/home/userName1/log.txt`.
- Include the conversion specifiers in the file name. For example:
  - To include date and time in the file name, use the date and time conversion specifiers: `log_%Y_%m_%d_%H_%M_%S.txt`. The conversion specifiers will be automatically replaced with the date and time when the program is initiated, resulting in `log_2017_11_21_09_41_00.txt`.
  - To include the process id in the file name, use the `%i` conversion specifier: `log_%Y_%m_%d_%H_%M_%S_%i.txt` for the result: `log_2017_11_21_09_41_00_21264.txt` when the process id is `21264`. When you have several processes running, using the process

id conversion specifier will prevent these processes from writing to the same file at the same time.

Note: The supported conversion specifiers are similar to the `strftime` function.

If the file already exists, the log will overwrite the existing file.

Note: These environmental variables are only checked once at the initialization. Any subsequent changes in these environmental variables will not be effective in the current run. Also note that these environment settings can be overridden by Method 2 below.

See also Table 3 for the impact on the performance of API logging using environment variables.

Table 3. API Logging Using Environment Variables

Environment variables	**CUDNN_LOGINFO_DBG=0**	**CUDNN_LOGINFO_DBG=1**
`CUDNN_LOGDEST_DBG` not set	No logging output No performance loss	No logging output No performance loss
`CUDNN_LOGDEST_DBG=NULL`	No logging output No performance loss	No logging output No performance loss
`CUDNN_LOGDEST_DBG=stdout` or `stderr`	No logging output No performance loss	Logging to `stdout` or `stderr` Some performance loss
`CUDNN_LOGDEST_DBG=filename.txt`	No logging output No performance loss	Logging to `filename.txt` Some performance loss

Method 2

Method 2: To use API function calls to enable API logging, refer to the API description of cudnnSetCallback() and cudnnGetCallback().

Chapter 15. Features Of RNN Functions

The RNN functions are:

- cudnnRNNForwardInference()
- cudnnRNNForwardTraining()
- cudnnRNNBackwardData()
- cudnnRNNBackwardWeights()
- cudnnRNNForwardInferenceEx()
- cudnnRNNForwardTrainingEx()
- cudnnRNNBackwardDataEx()
- cudnnRNNBackwardWeightsEx()

See the table below for a list of features supported by each RNN function:

Note:

For each of these terms, the short-form versions shown in the parenthesis are used in the tables below for brevity: `CUDNN_RNN_ALGO_STANDARD` (`_ALGO_STANDARD`), `CUDNN_RNN_ALGO_PERSIST_STATIC` (`_ALGO_PERSIST_STATIC`), `CUDNN_RNN_ALGO_PERSIST_DYNAMIC` (`_ALGO_PERSIST_DYNAMIC`), and `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION` (`_ALLOW_CONVERSION`).

Functions	Input/output layout supported	Supports variable sequence length in batch	Commonly supported

`cudnnRNNForwardInference`
`cudnnRNNForwardTraining`
`cudnnRNNBackwardData`
`cudnnRNNBackwardWeights`
	Only Sequence major, packed (non-padded)	Only with `_ALGO_STANDARD`
		Require input sequences descending sorted according to length
			Mode (cell type) supported:
			`CUDNN_RNN_RELU`, `CUDNN_RNN_TANH`, `CUDNN_LSTM`, `CUDNN_GRU`
			Algo supported[1] (see the table below for an

`cudnnRNNForwardInferenceEx` `cudnnRNNForwardTrainingEx`	▶ Sequence major unpacked	Only with `_ALGO_STANDARD`	

[1] Do not mix different algos for different steps of training. It's also not recommended to mix non-extended and extended API for different steps of training.

Functions	Input/output layout supported	Supports variable sequence length in batch	Commonly supported

`cudnnRNNBackwardDataEx`
`cudnnRNNBackwardWeightsEx`
	▶ Batch major unpacked[2]
	▶ Sequence major packed[2]
		For unpacked layout[2], no input sorting required.
		
		For packed layout, require input sequences descending sorted according to length
			elaboration on these algorithms):
			`_ALGO_STANDARD`, `_ALGO_PERSIST_STATIC`, `_ALGO_PERSIST_DYNAMIC`
			Math mode supported:
			`CUDNN_DEFAULT_MATH`, `CUDNN_TENSOR_O`
			(will automatically fall back if run on pre-Volta or if algo doesn't support Tensor Cores)
			`_ALLOW_CONVERSION` (may do down conversion to utilize Tensor Cores)
			Direction mode supported:
			`CUDNN_UNIDIRECTIONAL`,
			`CUDNN_BIDIRECTIONAL`
			RNN input mode:
			`CUDNN_LINEAR_INPUT`, `CUDNN_SKIP_INPUT`

The following table provides the features supported by the algorithms referred in the above table: `CUDNN_RNN_ALGO_STANDARD`, `CUDNN_RNN_ALGO_PERSIST_STATIC`, and `CUDNN_RNN_ALGO_PERSIST_DYNAMIC`.

Features	`_ALGO_STANDARD`	`_ALGO_PERSIST_STAT`	`_ALGO_PERSIST_DYNAMIC`
Half input Single accumulation Half output	Supported Half intermediate storage Single accumulation		
Single input Single accumulation Single output	Supported If running on Volta, with `CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION`[!], will down-convert and use half intermediate storage. Otherwise: Single intermediate storage Single accumulation		
Double input Double accumulation	Supported	Not Supported	Supported

[2] To use unpacked layout, user need to set `CUDNN_RNN_PADDED_IO_ENABLED` through `cudnnSetRNNPaddingMode()`.

Features	_ALGO_STANDARD	_ALGO_PERSIST_STAT	_ALGO_PERSIST_DYNAMIC
Double output	Double intermediate storage Double accumulation		Double intermediate storage Double accumulation
LSTM recurrent projection	Supported	Not Supported	Not Supported
LSTM cell clipping	Supported		
Variable sequence length in batch	Supported	Not Supported	Not Supported
Tensor Cores on Volta/ Xavier	Supported For half input/output, acceleration requires setting CUDNN_TENSOR_OP_MATH[3] or CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION [3] Acceleration requires inputSize and hiddenSize to be a multiple of 8 For single input/output, acceleration requires setting CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION[3] Acceleration requires inputSize and hiddenSize to be a multiple of 8		Not Supported, will execute normally ignoring CUDNN_TENSOR_OP_MATH[3] or _ALLOW_CONVERSION[3]
Other limitations		Max problem size is limited by GPU specifications.	Requires real time compilation through NVRTC

[3] CUDNN_TENSOR_OP_MATH or CUDNN_TENSOR_OP_MATH_ALLOW_CONVERSION can be set through cudnnSetRNNMatrixMathType().

Chapter 16. Mixed Precision Numerical Accuracy

When the computation precision and the output precision are not the same, it is possible that the numerical accuracy will vary from one algorithm to the other.

For example, when the computation is performed in FP32 and the output is in FP16, the `CUDNN_CONVOLUTION_BWD_FILTER_ALGO_0` (`ALGO_0`) has lower accuracy compared to the `CUDNN_CONVOLUTION_BWD_FILTER_ALGO_1` (`ALGO_1`). This is because `ALGO_0` does not use extra workspace, and is forced to accumulate the intermediate results in FP16, i.e., half precision float, and this reduces the accuracy. The `ALGO_1`, on the other hand, uses additional workspace to accumulate the intermediate values in FP32, i.e., full precision float.

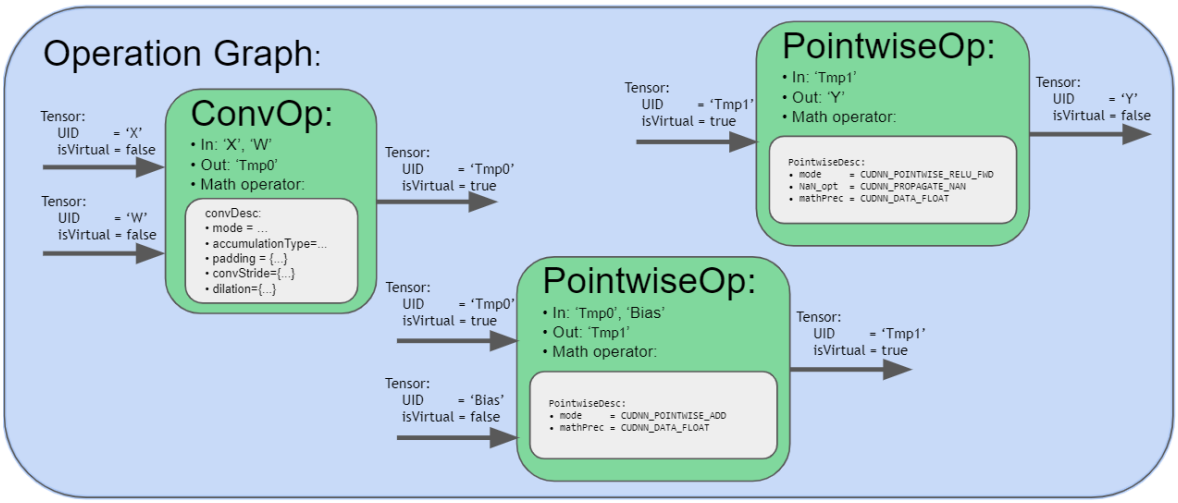
Chapter 17. Operation Fusion Via The Backend API

Introduced in cuDNN 8.0, operation fusion can be achieved via the backend API. The general workflow is similar to running unfused operations, except that instead of creating a single operation Operation Graph, the user may specify a multi-operation Operation Graph. Here we illustrate the flow via an example.

In the following example, the user would like to implement a fusion operation of convolution, bias, and activation.

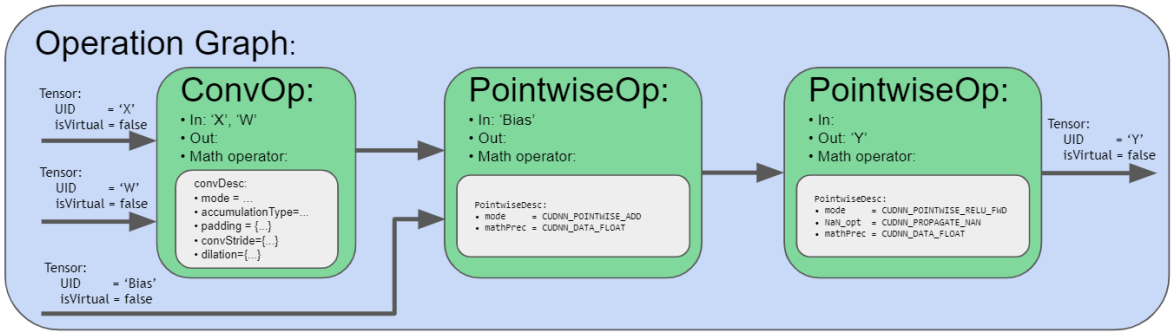
- First, the user should create three cuDNN backend operation descriptors - one convolution operation descriptor and two pointwise operation descriptors. Depending on the pointwise mode in the pointwise descriptor, a pointwise operation descriptor can be set up to describe an activation operation or a bias operation. By specifying the backend tensor *Tmp0* as both the output of the convolution operation and the input of the bias operation, this allows cuDNN to infer the dataflow between the operations. The same applies to tensor *Tmp1*. Here assume the user doesn't need the intermediate results *Tmp0* and *Tmp1* for any other use, then the user can specify them to be virtual tensors, so the memory I/Os can later be optimized out.
  - Note for the purpose of fusion, users should not construct in-place operations where any of the input UIDs matches any of its own output UIDs. Such in-place operations will be considered cyclic in later graph analysis and deemed unsupported.
  - Also note that the operation descriptors can be passed into cuDNN in any order, as the tensor UIDs are enough to determine the dependencies in the graph.

Figure 9. A set of operation descriptors the user passes to the operation graph



- Second, upon finalizing the operation graph, cuDNN will perform the dataflow analysis to establish the dependency relationship between operations and connect the edges, as illustrated in the figure below. In this step, cuDNN will also perform various checks to confirm the validity of the graph.

Figure 10. The operation graph after finalization



- Third, with the finalized operation graph, there are two options:
  - For most users that prefer cuDNN to recommend the best engine and knob choices, they can query cuDNN's heuristics to get a list of engine configs and choose from them. After that, the user can construct the execution plan using the chosen engine config. Note the heuristics support for fusion use cases are not yet available. This will be available in the coming releases.
  - For expert users, they can query the engines that can support this operation graph. For each engine, the user can further query the numerical notes and adjustable knobs. Numerical notes would inform the user about the numerical behavior of the engine such as whether it does datatype down conversion at the input or during output

reduction. The adjustable knobs allow fine grained control of the engine's behavior and performance. With the engine choice and the knob choice determined, the user can construct the backend engine, backend engine config, and further the execution plan.

Note for operation fusion use cases, there are two different mechanisms in cuDNN to support them. First, there are engines containing offline compiled kernels that can support certain fusion patterns. These engines try to match the user provided operation graph with their supported fusion pattern. If there is a match, then that particular engine is deemed suitable for this use case. In addition, there are also runtime fusion engines to be made available in the upcoming releases. Instead of passively matching the user graph, such engines actively walk the graph and assemble code blocks to form a CUDA kernel and compile on the fly. Such runtime fusion engines are much more flexible in its range of support. However, because the construction of the execution plans requires runtime compilation, the one-time CPU overhead is higher than the other engines.

- Finally, with the execution plan constructed and when it comes time to run it, the user should construct the backend variant pack by providing the workspace pointer, an array of UIDs, and an array of device pointers. The UIDs and the pointers should be in the corresponding order. With the handle, the execution plan and variant pack, the execution API can be called and the computation is carried out on the GPU.

The table below briefly summarizes the current fusion support in cuDNN. We will be adding additional support in the upcoming releases. We welcome feature suggestions. For feedback, email cudnn@nvidia.com.

Fusion Graph Pattern	Supported Device Compute Capabilities	Supported Data Config and Layout	Supported Engine Types
`Conv_Bias_Add_activation`	All that cuDNN supports	Same as `cudnnConvolutionBiasActivationForward()`	Pattern matching engines, runtime fusion engines[4]
`Scale_Bias_Activation_conv_bn_stats`	Compute capability 70 or above	`PSEUDO_HALF_CONFIG`, NHWC layout	Pattern matching engines, runtime fusion engines[1]
`Convolution_Pointwise`[1]	Compute capability 75 or above	Flexible	Runtime fusion engines[1]
`Gemm_Pointwise`[1]	Compute capability 75 or above	Flexible	Runtime fusion engines[1]

[4] As of cuDNN 8.0.0, the runtime fusion engines are not yet available. They will be made available in the upcoming releases.

Chapter 18. Troubleshooting

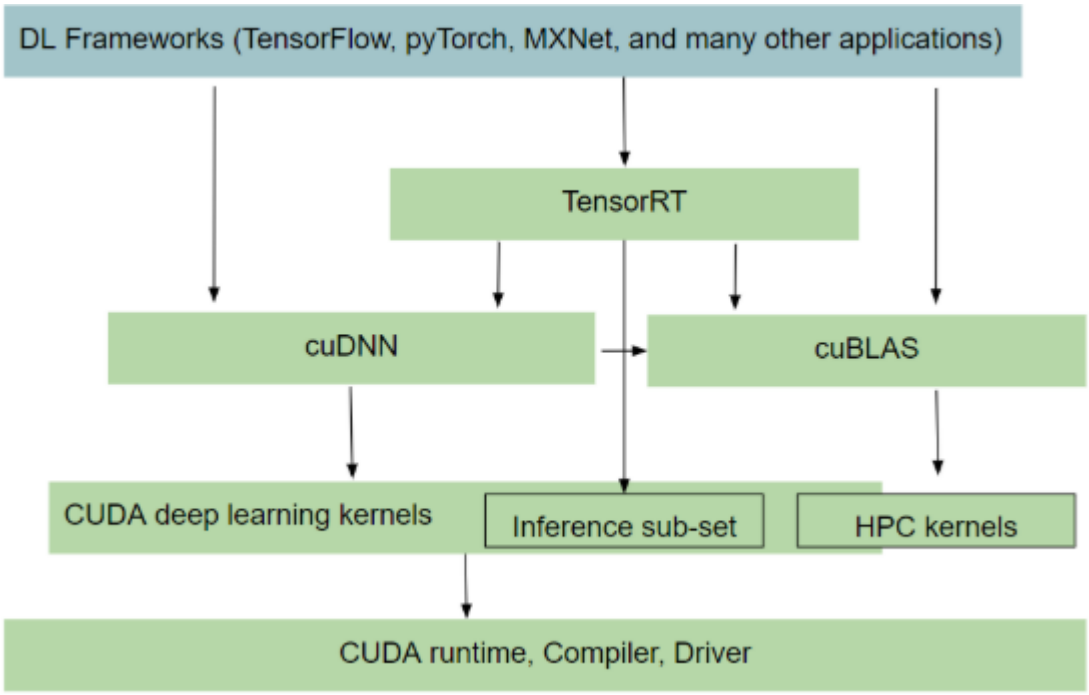
The following sections help answer the most commonly asked questions regarding typical use cases.

18.1. FAQs

Q: Where in the software stack does cuDNN sit? What is the interaction between CUDA, cuDNN, and TensorRT?

A: The following graphic shows how cuDNN relates to other software in the stack.

Figure 11. Software stack with cuDNN.



Q: I'm not sure if I should use cuDNN for inference or training. How does it compare with TensorRT?

A: cuDNN provides the building blocks for common routines such as convolution, pooling, activation and RNN/LSTMs. You can use cuDNN for both training and inference. However, where it differs from TensorRT is that the latter (TensorRT) is a programmable inference accelerator; just like a framework. TensorRT sees the whole graph and optimizes the network by fusing/combining layers and optimizing kernel selection for improved latency, throughout, power efficiency and for reducing memory requirements.

A rule of thumb you can apply is to check out TensorRT, see if it meets your inference needs, if it doesn't, then look at cuDNN for a closer, more in-depth perspective.

Q: How does heuristics in cuDNN work? How does it know what is the optimal solution for a given problem?

A: NVIDIA actively monitors the Deep Learning space for important problem specifications such as commonly used models. The heuristics are produced by sampling a portion of these problem specifications with available computational choices. Over time, more models are discovered and incorporated into the heuristics.

Q: Is cuDNN going to support running arbitrary graphs?

A: No, we don't plan to become a framework and execute the whole graph one op at a time. At this time, we are focused on a subgraph given by the user, where we try to produce an optimized fusion kernel. We will document what the rules regarding what can be fused and what cannot. The goal is to support general and flexible fusion, however, it will take time and there will be limits in what it can do in the cuDNN version 8.0.0 launch.

Q: What's the difference between TensorRT, TensorFlow/XLA's fusion, and cuDNN's fusion?

A: TensorRT and TensorFlow are frameworks; they see the whole graph and can do global optimization, however, they generally only fuse pointwise ops together. On the other hand, cuDNN targets a subgraph, but can fuse convolutions with pointwise ops, thus providing potentially better performance. CuDNN fusion kernels can be utilized by TensorRT and TensorFlow/XLA as part of their global graph optimization.

Q: Can I write an application calling cuDNN directly?

A: Yes, you can call the C/C++ API directly. Usually, data scientists would wait for framework integration and use the Python API which is more convenient. However, if your use case requires better performance, you can target the cuDNN API directly.

Q: How does mixed precision training work?

A: Several components need to work together to make mixed precision training possible. CuDNN needs to support the layers with the required datatype config and have optimized kernels that run very fast. In addition, there is a module called automatic mixed precision (AMP) in frameworks which intelligently decides which op can run in a lower precision without affecting convergence and minimize the number of type conversions/transposes in the entire graph. These work together to give you speed up. For more information, see Mixed Precision Numerical Accuracy.

Q: How can I pick the fastest convolution kernels with cuDNN version 8.0.0?

A: In the API introduced in cuDNN v8, convolution kernels are grouped by similar computation and numerical properties into engines. Every engine has a queryable set of performance tuning knobs. A computation case such as a convolution operation graph can be computed using different valid combinations of engines and their knobs, known as an engine configuration. Users can query an array of engine configurations for any given computation case ordered by performance, from fastest to slowest according to cuDNN's own heuristics. Alternately, users can generate all possible engine configurations by querying the engine count and available knobs for each engine. This generated list could be used for auto-tuning or the user could create their own heuristics.

Q: How do I build the cuDNN version 8.0.0 split library?

A: cuDNN v8.0 library is split into multiple sub-libraries. Each library contains a subset of the API. Users can link directly against the individual libraries or link with a `dlopen` layer which follows a plugin architecture.

To link against an individual library, users can directly specify it and its dependencies on the linker command line. For example, for infer libraries: `-lcudnn_adv_infer`, `-lcudnn_cnn_infer`, or `-lcudnn_ops_infer`.

For all libraries, `-lcudnn_adv_train`, `-lcudnn_cnn_train`, `-lcudnn_ops_train`, `-lcudnn_adv_infer`, `-lcudnn_cnn_infer`, and `-lcudnn_ops_infer`.

The dependency order is documented in the cuDNN 8.0.0 Preview Release Notes and the cuDNN API Reference.

Alternatively, the user can continue to link against a shim layer (`-libcudnn`) which can `dlopen` the correct library that provides the implementation of the function. When the function is called for the first time, the dynamic loading of the library takes place.

Linker argument:

```
-lcudnn
```

Q: What are the new APIs in cuDNN version 8.0.0?

A: The new cuDNN APIs are listed in the cuDNN 8.0.0 Release Notes as well as in the API Changes For cuDNN 8.0.0.

18.2. How Do I Report A Bug?

We appreciate all types of feedback. If you encounter any issues, please report them by following these steps.

1. Register for the NVIDIA Developer website.
2. Log in to the developer site.
3. Click on your name in the upper right corner.
4. Click **My account** > **My Bugs** and select **Submit a New Bug**.
5. Fill out the bug reporting page. Be descriptive and if possible, provide the steps that you are following to help reproduce the problem.
6. Click **Submit a bug**.

18.3. Support

Support, resources, and information about cuDNN can be found online at https://developer.nvidia.com/cudnn. This includes downloads, webinars, NVIDIA Developer Forums, and more.

For questions or to provide feedback, please contact cuDNN@nvidia.com.

Chapter 19. Acknowledgments

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