



Lattice sensAI Machine Learning Engine Simulator

User Guide

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Inclusive Language

This document was created consistent with Lattice Semiconductor's inclusive language policy. In some cases, the language in underlying tools and other items may not yet have been updated. Please refer to Lattice's inclusive language [FAQ 6878](#) for a cross reference of terms. Note in some cases such as register names and state names it has been necessary to continue to utilize older terminology for compatibility.

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Abbreviations in This Document

A list of abbreviations used in this document.

| Abbreviation | Definition |
|--------------|--------------------------------|
| Conv2D | 2D Convolutional Layer |
| CPU | Central Processing Unit |
| FPGA | Field Programmable Gate Arrays |
| GPU | Graphics Processing Unit |
| LSQ | Learned Step Size Quantization |

1. Introduction

A simulator is a tool that allows running networks in software and getting the same results as if they were run on a Lattice Semiconductor FPGA. The Simulator can be used to investigate why and where results differ between CPU or GPU networks and the FPGA.

We expect results to differ because the FPGA does not represent values with floating point numbers but uses its own custom fixed-point representations. This gives slight changes to the results of all calculations, which can add up over the course of a run. It also means that values can more easily exceed their allowed range, leading to saturation.

With the Simulator, we can analyze not only the final output of the network, but also the results of each layer individually.

The Machine Learning Engine Simulator is implemented in C++, but with wrappings that allow it to be imported as a Python package for use in Python scripts.

2. Simulator Features

2.1. Core Features

- For any given input and supported network, the simulator will produce outputs that matches the results obtained on the FPGA platform.
- The simulator can be run in both FPGA fixed-point (FPQ and LSQ) and floating-point number modes.
- The simulator supports more than 20 different layer types.
- The simulator supports networks with multiple input layers.
- The simulator supports networks with multiple output layers.
- The simulator is fast. It can be used in real time with networks of considerable sizes.
- It comes in an easy-to-use Python package that can be imported and used in any script.
- It can be used both on Windows and Linux.

2.2. Diagnostic Features

Diagnostic features are divided in three parts: Output Inspection, Outputs Comparison and Saturation Statistics.

2.2.1. Output Inspection

- The simulator has two run configurations: output only and layer by layer results.
- In the first configuration, only the results of the last layers of the network are returned.
- In the second configuration, the simulator returns an object that contains results for each layer individually and that provides methods to query and retrieve the output of any layer in the network.

2.2.2. Outputs Comparison

The simulator allows for side-by-side comparison of two simulation runs, down to the individual layer level. This feature enables users to analyze the differences in model behavior when running in different modes, such as comparing floating-point number mode to FPGA mode to understand how the model performs on hardware.

The simulator can compare the two simulation runs using aggregate metrics. One example is to determine the largest absolute difference between the results of the tenth convolution layer when running in FPGA mode versus floating-point number mode. This metric provides a quantitative measure of the discrepancy between the two implementations. [Table 2.1.](#) lists the supported aggregate metrics.

Table 2.1. Supported Aggregate Metrics

| Metric Name | Metric |
|-------------|--------------------------------|
| RMS | Root Mean Square Error |
| MAXE | Maximum Absolute Error |
| MAE | Mean Absolute Error |
| RMSPE | Root Mean Square Percent Error |
| MAXPE | Max Absolute Percent Error |

Comparison can be made element-wise between layers. For example, getting a vector representing the differences between two runs of the simulator for a specific layer in the network. Vectors in element-wise comparison operations can be clipped to the range of the layer under study. This is useful when comparing between floating point number results and FPGA mode results to bring the floating-point number results into the valid range and avoid excessive differences due to saturation. Table 2.2. lists the supported element-wise metrics.

Table 2.2. Supported Element-Wise Metrics

| Feature | Software Default Mode State (Programmed) |
|----------|---|
| Simple | Raw difference between results and reference results = $R - Ref$ |
| Absolute | Absolute differences between results and reference results = $abs(R - Ref)$ |
| Relative | Fraction of the raw difference between results over reference results = $(R - Ref) / Ref$ |

Note: For networks trained with LSQ, comparisons between Float mode and FPGA mode are not meaningful for intermediate layers because LSQ FPGA mode results are integers, not equivalent floating-point representations. To compare LSQ with Float, use the `report_in_float` flag when loading the network to display all layer results converted to float space.

2.2.3. Saturation Statistics

A results object obtained from a run of the simulator on some input can be queried to retrieve a saturation object representing saturation - a measure of clipping - on a layer-by-layer basis. For a value outside its allowed range, saturation is defined as the absolute difference between the value and the closest limit of the range.

Supported saturation statistics include the following saturation object properties as shown in Table 2.3.

Table 2.3. Saturation Statistics

| Feature | Software Default Mode State (Programmed) |
|-----------------|--|
| saturation | Total saturation for the given layer. |
| count | Number of times a saturation was observed while computing the layer. |
| avg | Average saturation in the given layer. Essentially saturation divided by count. |
| ad_ops | Number of addition operations performed by the layer. Estimate of amount of computation. |
| sat_rel_add_ops | Total saturation for the given layer divided by the number of add operations. |
| range | Allowed range of the values for the given layer. |
| sat_rel_range | Average saturation divided by the range of the layer. |

Saturation statistics can be returned for a particular layer in the network as above, or for a particular layer type in the network. In that case, the statistics are the same, only the values are aggregated by layer type.

Note: Saturation is not supported in LSQ mode.

2.2.4. Weights Manipulation Features

The simulator provides a way to retrieve and change weights in a model. Layer types supporting this feature are layers with weights:

- Convolution 2D and Depth Wise Convolution 2D
- Batch Normalization
- Dense

This feature is useful in at least two cases:

- Diagnostics — One run of the simulator can be made with a set of weights and another with another set of weights only to compare differences between the two runs on a layer-by-layer basis.
- Test set evaluation — At any time during training, it might be useful to determine the error of the current model on the test set as if on FPGA. To do that we need the ability to change the weights of the model if currently loaded in the simulator.

Note: Weight Manipulation (specifically changing weights) is not supported in LSQ mode.

3. Installation

3.1. Requirements

Python versions 3.10 and 3.11 are supported.

3.2. Installation Steps

The installation process for the simulator consists of installing a Python wheel. This way, it is not necessary to manually install dependencies.

To install the simulator wheel, it is strongly recommended to first create a Python environment using *venv* or *conda*. Once the environment is created, you need to activate it. Then, follow the instructions below depending on your operating system of choice.

3.2.1. Windows

To install the simulator wheel in Windows, open a command line or PowerShell prompt, activate your Python environment if not already activated, and type:

```
python -m pip install ml_engine_simulator-x.x.x-py3-none-win_amd64.whl
```

Note: x.x.x must be replaced by your current version of the simulator.

3.2.2. Linux

To install the simulator wheel in Linux, open a shell and first install *libs2*. This can be done, for example here on Ubuntu, by issuing these commands:

```
sudo apt-get update  
sudo apt-get install libs2
```

Then activate your Python environment if not already activated and install the simulator wheel:

```
python3 -m pip install ml_engine_simulator-x.x.x-py3-none-linux_x86_64.whl
```

Note: x.x.x must be replaced by your current version of the simulator.

3.3. Using and Importing the Simulator

To use the simulator, make sure your Python environment is activated, run Python and import the package:

```
import ml_engine_simulator.network as sim
```

When performing the steps above and regardless of your operating system, it is possible to import *ml_engine_simulator.network* from any directory, provided your Python environment where the simulator is installed is activated.

4. Supported Layer Types

4.1. Float Mode

In floating-point mode, the simulator supports all layers described in [Table 4.1](#) and [Table 4.2](#), albeit in floating-point values (FP32), meaning that number representations or output width are meaningless in that mode.

4.2. FPQ Mode

This section enumerates the layer types supported by the simulator in FPQ mode. [Table 4.1](#) summarizes the layer types. Note that in this table:

- Layer refers to the type of layer
- Input Rep is the input fixed-point number representation as accepted by the layer
- Weights Rep is the fixed-point number representation used to quantize the weights
- Work Rep is the fixed-point number representation used to carry out operations
- Output Rep is the output fixed point number representation as returned by the layer
- Comments are any further comments where applicable

Representations in the [Table 4.1](#) are denoted as:

- X.Y means *X* integer bits, *Y* fractional bits.
- Representations are either *signed* or *unsigned* as indicated in [Table 4.1](#).
- Scale, for example a scale of 0.5, means values are further multiplied by the scale value.

Some examples:

- Unsigned 1.7 range = [0.0, 2.0) with a step size of 1/128 → [0.0, 2 - 1/128]
- Signed 0.7 with 0.5 scale range = [-0.5, 0.5) with a step size of 1/256 → [-0.5, 0.5 - 1/256]
- Signed 5.10 range = [-32, 32) with a step size of 1/1024 → [-32, 32 - 1/1024]

Some considerations regarding representations:

- Representations are specified in a quantization file. The ones in [Table 4.1](#) are currently in use. There should be no need to change those.
- The *Quantize* version of some layer types below can have their own representation, rather than per layer type. However, the simulator currently uses the representations in [Table 4.1](#), which are per layer type for now.

Table 4.1. MachXO3D Feature Row Elements - FPQ

| Layer | Input Rep | Weights Rep | Work Rep | Output Rep | Comments |
|---|-----------------------------------|---------------------------|-----------------|----------------------------------|---|
| InputLayer | Unsigned 1.7 | None | None | Unsigned 1.7 | – |
| Conv2D sensAI>QuantizeConv2D | Unsigned 1.7 or Signed 0.7 | Signed 0.7 (scale 0.5) | Signed 16.15 | Signed 5.10 | – |
| DepthWiseConv2D sensAI>QuantizeDepthwiseConv2D | Unsigned 1.7 or Signed 5.10 | Signed 0.7 (scale 0.5) | Signed 16.15 | Signed 5.10 | Input representation depends on previous layer |
| Dense sensAI>QuantizeDense | Unsigned 1.7 | Signed 0.7 (scale 0.5) | Signed 24.15 | Signed 5.10 or Signed 2.13 | Output representation is 2.13 when Dense is followed by QuantizeActivation sigmoid, 5.10 otherwise. |

| Layer | Input Rep | Weights Rep | Work Rep | Output Rep | Comments |
|---|-----------------------------------|---------------------------|--------------|-----------------------------------|---|
| | | | | | Support for stacked dense layers is experimental now. |
| MaxPooling2D | Unsigned 1.7 | None | Unsigned 1.7 | Unsigned 1.7 | – |
| ReLU (activation) sensAI>QuantizeActivation (ReLU) | Unsigned 1.7 or Signed 5.10 | None | Unsigned 1.7 | Unsigned 1.7 | Input representation is 5.10 when following Dense. It is 1.7 to chain with Lambda otherwise. |
| Add sensAI>QuantizeAdd | Unsigned 1.7 or Signed 0.7 | None | Unsigned 1.7 | Unsigned 1.7 | – |
| BatchNormalization sensAI>QuantizeBatchNormalization | Signed 5.10 | Signed 5.10 | Signed 5.10 | Signed 5.10 | – |
| Lambda | Signed 5.10 or Unsigned 1.7 | None | Unsigned 1.7 | Unsigned 1.7 | Input representation depends on previous layer |
| Concatenate sensAI>QuantizeConcat | Any | None | None | Same as input | Layer simply moves data |
| Flatten | Any | None | None | Same as input | Layer simply moves data |
| Slicing | Any | None | None | Same as input | Layer simply moves data |
| Focus | Any | None | None | Same as input | Layer simply moves data |
| Resizing | Unsigned 1.7 | Signed 0.7 (scale 0.5) | Signed 16.15 | Unsigned 1.7 | – |
| Reciprocal | Signed 5.10 | None | Signed 5.10 | Signed 5.10 | $f(x) = 1/x$. Not supported in FPGA. |
| Multiply | Signed 5.10 or Unsigned 1.7 | None | Signed 5.10 | Signed 5.10 or Unsigned 1.7 | Input representation depends on previous layer Output representation is 1.7 if layer is followed by Lambda. Not supported in FPGA. |
| SensAI> QuantizeActivation (sigmoid) | Signed 2.13 | None | None | Signed 5.10 | – |
| Dropout | Any | None | None | Same as input | This layer is not considered by the simulator. It is as if it was nonexistent in the network. |
| sensAI>QuantizeOutput | Any | None | None | Signed 5.10 | – |
| SiLU | Signed 2.13 | None | Signed 0.7 | Unsigned 1.7 | The work rep is the actual rep used to quantize the values in the table; the output rep is only used for chaining. |

| Layer | Input Rep | Weights Rep | Work Rep | Output Rep | Comments |
|---------|-----------|-------------|--------------|----------------------------|-------------------------|
| Split | Any | None | None | Same as input | Layer simply moves data |
| Permute | Any | None | None | Same as input | Layer simply moves data |
| Reshape | Any | None | None | Same as input | Layer simply moves data |
| GEMM | Any | Signed 5.10 | Signed 16.15 | Unsigned 1.7 or signed 0.7 | – |
| Softmax | Any | None | Signed 12.12 | Unsigned | – |

4.3. LSQ Mode

This section enumerates the layer types supported by the simulator in LSQ mode. Table 4.2 summarizes the layer types. Note that in this table:

- Layer refers to the type of layer.
- Output width refers to the number of bits used by values returned by the layer.
- Comments are any further comments where applicable.

Table 4.2. MachXO3D Feature Row Elements - LSQ

| Layer | Output Width | Comments |
|---|--------------------------------|--|
| InputLayer | Unsigned 8 | – |
| Conv2D SensAI>QuantizeConv2D | Signed 16 | Any kernel size and stride supported. |
| DepthWiseConv2D SensAI>QuantizeDepthwiseConv2D | Signed 16 | Any kernel size and stride supported. |
| Dense SensAI>QuantizeDense | Signed 16 | Support for stacked dense layers is experimental now. |
| MaxPooling2D | Unsigned 8 | Any pooling region supported. “Spatial Pyramidal Pooling – Fast” (aka SPPF) is supported. |
| ReLU (activation) SensAI>QuantizeActivation (ReLU) | Unsigned 8 | – |
| Add SensAI>QuantizeAdd | Signed 8 | – |
| BatchNormalization sensAI>QuantizeBatchNormalization | Signed 16 | – |
| Concatenate SensAI>QuantizeConcat | Same as input | Layer simply moves data |
| Flatten | Same as input | Layer simply moves data |
| Slicing | Same as input | Layer simply moves data |
| Focus | Same as input | Layer simply moves data |
| UpSampling2D | Same as input or Unsigned 8 | Both nearest neighbors and bilinear interpolation are supported. Output width is 8 bits (unsigned) when in bilinear interpolation mode; same as input in nearest neighbors’ mode. |

| Layer | Output Width | Comments |
|--------------------------------------|-------------------------------|--|
| Resizing ¹ | Same as input or Unsigned 8 | Both nearest neighbors and bilinear interpolation are supported. Output width is 8 bits (unsigned) when in bilinear interpolation mode; same as input in nearest neighbors' mode. |
| Reciprocal | Signed 16 | $f(x) = 1/x$. Untested in LSQ. Not supported on FPGA. |
| Multiply | Signed 16 | Untested in LSQ. Not supported on FPGA. |
| SensAI> QuantizeActivation (sigmoid) | Signed 16 | – |
| Dropout | Same as input | This layer is not considered by the simulator. It is as if it was nonexistent in the network. |
| GlobalAveragePooling2D | Signed or Unsigned 8 | Averages over channels. Signed or unsigned depends on input. |
| sensAI>QuantizeOutput | Signed 16 bits in 5.10 format | QuantizeOutput uses signed 16 bits but returns its results in 5.10 fixed-point format. It is the only layer type that returns values like this in LSQ. |
| SiLU | Signed 8 | – |
| Split | Same as input | Layer simply moves data |
| Permute | Same as input | Layer simply moves data |
| Reshape | Same as input | Layer simply moves data |
| GEMM | Unsigned or Signed 8 | – |
| SoftMax | Unsigned 8 | – |

Note:

1. Resizing is another term for UpSampling2D.

5. Special Considerations

5.1. Network Structure

This section enumerates some special considerations related to network structure. If a network structure is not compatible with the simulator, it will fail loading the network with some error messages.

5.1.1. Convolution Layers Bias (FPQ)

If a convolution layer (Conv2D or Depth Wise Conv2D) uses a bias, it must be followed by a batch normalization layer, or the network would not load. This is because convolution layers cannot handle a bias directly. When they have a bias, the value of that bias is used to update the following batch normalization layer offset. The bias is absorbed there. If no batch normalization layer follows, the bias could not be considered.

5.1.2. Unsupported Layer Types

The simulator does not load a network that has an unsupported layer type in it.

5.1.3. General Network Structure

The simulator will reject a network if it has structural issues such as but not limited to incompatible dimensions from layer to layer and wrong children count for certain layers.

5.2. Quantization File

5.2.1. Absence of a Quantization File

The simulator needs a quantization file to load networks. You do not need to create this file. It is distributed with the simulator and its path can be obtained by calling the Python function.

```
get_default_quant_file()
```

This file describes the fixed-point number representation (and therefore output width) used by the various supported layer types.

5.3. Specific Layer Type Considerations

5.3.1. Multiply Layer

For an input of dimension (H, W, C), the multiply layer supports a second operand of dimension (H, W, C) or, with stacking, (H, W, 1). Any other configuration of input dimensions will result in the network not loading.

Note: This layer was not tested with LSQ but is expected to work.

5.4. Input and Output

5.4.1. Input Dimensions

The simulator takes its input in the NHWC format for the *Run* function or HWC format for *run_one_frame*. See API Reference manual.

5.4.2. Output Dimensions

The simulator will return its output as a 3D tensor (numpy array) in the HWC format always. This is the case even if the expected output is a vector and not an image. For example, for a column vector of size 4 and 1 channel, the simulator will return an output with dimensions [4, 1, 1]. For a row vector, it would be [1, 4, 1].

5.4.3. Output Format

The format of the output is *float32*.

Reference

- [Lattice Insights](#) for Lattice Semiconductor training courses and learning plans

Technical Support Assistance

Submit a technical support case through www.latticesemi.com/techsupport.

For frequently asked questions, refer to the Lattice Answer Database at www.latticesemi.com/Support/AnswerDatabase.

Revision History

Revision 1.1, December 2025

| Section | Change Summary |
|------------------------------------|---|
| All | <ul style="list-style-type: none"> Updated document title to <i>Lattice sensAI Machine Learning Engine Simulator</i>. Minor editorial fixes. |
| Abbreviations in This Document | <ul style="list-style-type: none"> Removed <i>ML</i>. Added <i>LSQ</i>. |
| Simulator Features | <ul style="list-style-type: none"> Updated Core Features section. Added note for Table 2.2. Supported Element-Wise Metrics, <i>For networks trained with LSQ, comparisons between Float mode and FPGA mode are not meaningful for intermediate layers because LSQ FPGA mode results are integers, not equivalent floating-point representations. To compare LSQ with Float, use the report_in_float flag when loading the network to display all layer results converted to float space.</i> Added note in Saturation Statistics section, <i>Saturation is not supported in LSQ mode.</i> Added note in Weights Manipulation Features section, <i>Weight Manipulation (specifically changing weights) is not supported in LSQ mode.</i> |
| Installation | Updated Python versions in Requirements section. |
| Supported Layer Types | <ul style="list-style-type: none"> Added Float Mode section. In FPQ Mode: <ul style="list-style-type: none"> Added this section. Updated Table 4.1. MachXO3D Feature Row Elements - FPQ. Added LSQ Mode section. |
| Specific Layer Type Considerations | <ul style="list-style-type: none"> In Network Structure section: <ul style="list-style-type: none"> Updated the title of Convolution Layers Bias (FPQ) section. Updated the content in Absence of a Quantization File. In Specific Layer Type Considerations: <ul style="list-style-type: none"> Removed <i>Dense Layer</i> section. Added note in Multiply Layer, <i>This layer was not tested with LSQ but is expected to work.</i> Updated content of Input Dimensions and Output Format sections. |
| Reference | Updated reference. |

Revision 1.0, November 2024

| Section | Change Summary |
|---------|------------------|
| All | Initial release. |

