

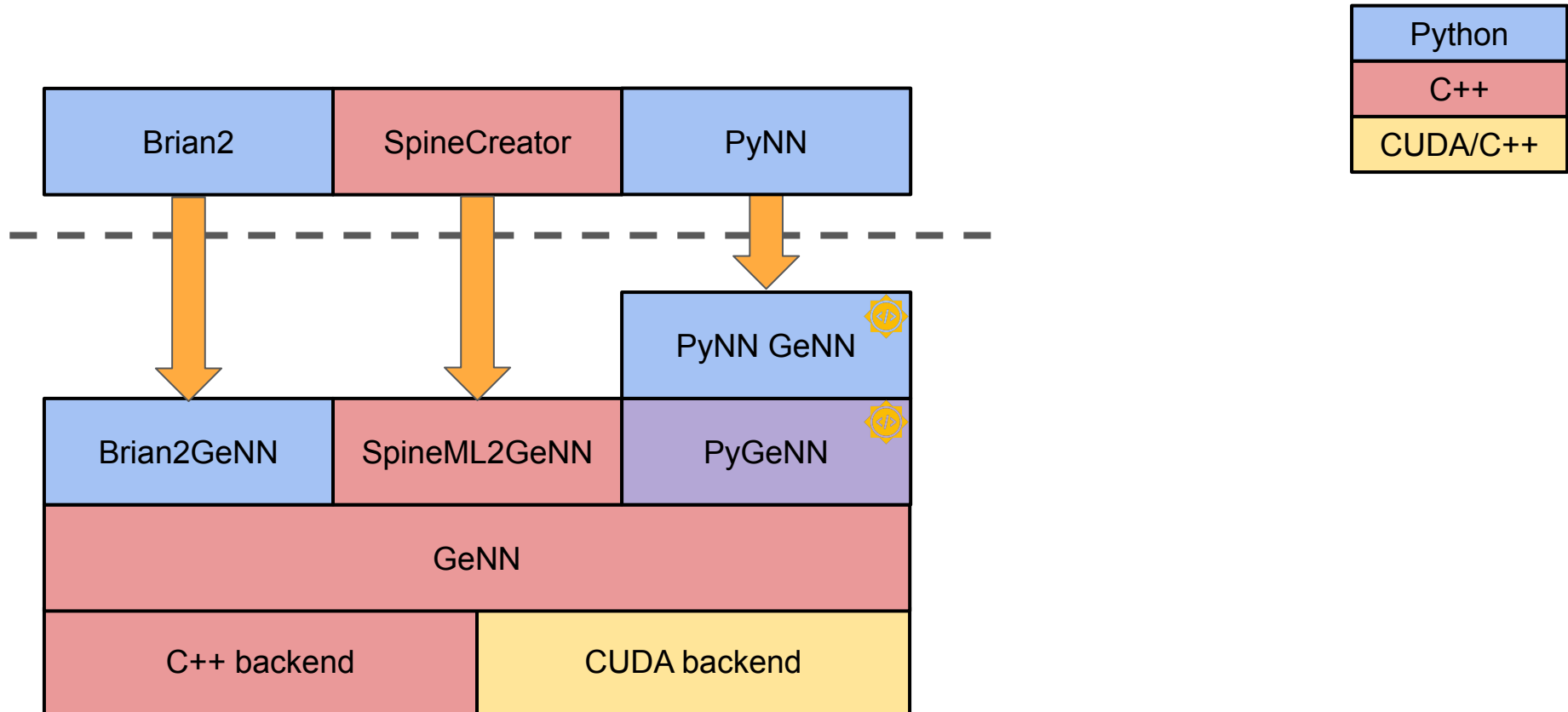
# Spike-based machine learning with GeNN

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# GeNN

- Cross-platform C++ library for generating optimised CUDA code for GPU accelerated SNN simulations.
- Can also generate C++ code for testing on computers without GPUs (e.g. here with your laptops!)
- Hopefully you've learnt all about it in our talks earlier in the week!
- All GeNN features are now available from Python for easier interoperability with other ML and Computational Neuroscience tools

# The GeNN ecosystem



# Installation

# CUDA on Linux

- Each version of CUDA only supports a subset of GCC versions so if you have a very old or very bleeding edge OS you may need to install an additional version of GCC.
- Installing CUDA via the NVIDIA proprietary packages tends to work best if your OS is supported.
- Ensure that the `CUDA_PATH` environment variable is set

# CUDA on Windows

- CUDA is nicely integrated into Visual Studio and provided graphical debugging and profiling tools
- Historically, because Visual Studio is frequently updated, compiler/CUDA version mismatches were more prevalent than on Linux **but**, as of CUDA 10 and Visual Studio 2017, this no longer appears to be the case!
- If installing from scratch we recommend:
  - CUDA 10.1
  - Visual Studio 2017

# CUDA on Mac

- Sadly Apple hasn't built any machines with NVIDIA GPUs since 2014
- However, if you're lucky enough to have:
  - MacBook Pro (Retina, 15-inch, Late 2013)
  - MacBook Pro (Retina, 15-inch, Mid 2014)
  - Equivalent iMac models (probably not with you!)
- You **may** have a NVIDIA GPU that's usable with the current version of CUDA!
- Ensure that the `CUDA_PATH` environment variable is set



# Windows notes

- PyGeNN requires at least Python 3.5 and Visual Studio 2015 installed
- I recommend using Anaconda for Python development on Windows
- You should install CUDA **after** Visual Studio so they are correctly integrated
- PyGeNN should be used from a command prompt with Python **and** Visual studio properly configured i.e. by activating conda within a Visual Studio "x64 Native Tools Command Prompt"



# Installing PyGeNN from binary wheels

1. Select a suitable wheel from the latest release available at <https://github.com/genn-team/genn/releases>

For example, if you have a Linux system with Python 3.7, you would pick `pygenn-0.2-cp37-cp37m-linux_x86_64.whl`

Note: the Mac OS X wheel are built for CUDA 9, all others for CUDA 10

2. Install the wheel using pip e.g.

```
pip install pygenn-0.2-cp37-cp37m-linux_x86_64.whl
```

# Installation from source on Linux/Mac

1. Download latest release of GeNN from <https://github.com/genn-team/genn/releases>
2. Make sure you have swig installed
3. From GeNN directory, build as a dynamic library, directly into the PyGeNN directory using:  
`make DYNAMIC=1`  
`LIBRARY_DIRECTORY=`pwd` /pygenn/genn_wrapper/`
4. Build and install python module with setuptools using:  
`python setup.py develop`

# Installation from source on Windows

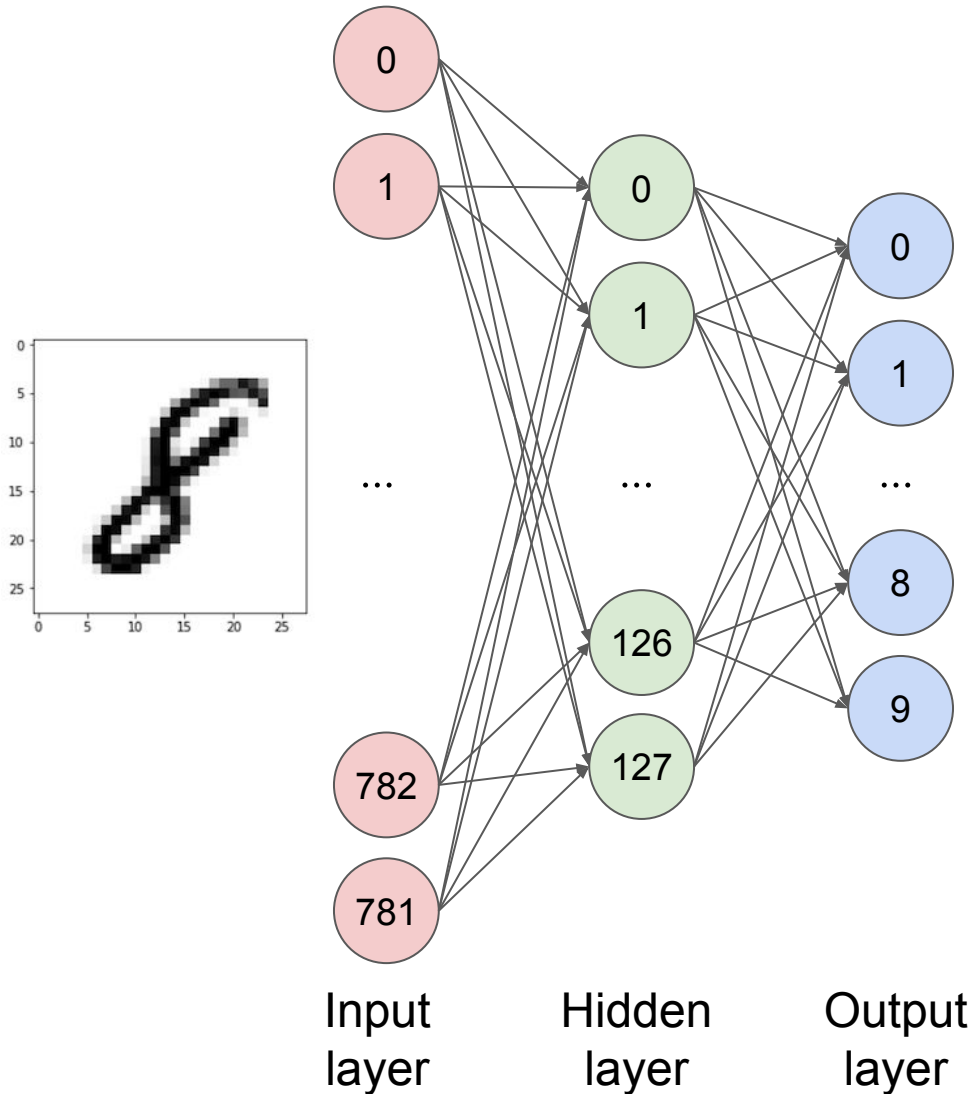
1. Download latest release of GeNN from <https://github.com/genn-team/genn/releases>
2. Make sure you have swig installed
3. From GeNN directory, build as a dynamic library using:  
`msbuild genn.sln /t:Build /p:Configuration=Release_DLL`
4. Copy the newly built DLLs into pygenn using  
`copy /Y lib\genn*Release_DLL.* pygenn\genn_wrapper`
5. Build and install python module with setuptools using:  
`python setup.py develop`

# Tutorial repository

- Checkout from:  
[https://github.com/neworderofjamie/pygenn\\_ml\\_tutorial](https://github.com/neworderofjamie/pygenn_ml_tutorial)
- Contains
  - `testing_images.npy` and `testing_labels.npy` - testing portion of MNIST dataset
  - `weights_0_1.npy` and `weights_1_0.npy` - weights trained in Keras
  - `tutorial_1.py` and `tutorial_2.py` - Code for this tutorial
- Test your installation with:  
`python tutorial_1.py`

# Tutorial: MNIST inference

# Part 0: Training the ANN



- Not state-of-the-art!
- I have already done this part for you!
- Achieves 97.6% accuracy on MNIST

# Part 1: Classifying a single image

1. Basics of using PyGeNN
2. Building a spiking network based on ANN
3. Recording spikes resulting from presenting single MNIST digit

Import some standard Python packages

```
import numpy as np  
from os import path
```

```
from pygenn.genn_model import (create_custom_neuron_class,  
                               create_custom_current_source_class,  
                               GeNNModel)  
from pygenn.genn_wrapper import NO_DELAY
```

Import some useful  
PyGeNN components



```
import numpy as np
from os import path

from pygenn.genn_model import (create_custom_neuron_class,
                                create_custom_current_source_class,
                                GeNNModel)
from pygenn.genn_wrapper import NO_DELAY
```

```
# -----
# Parameters
# -----
```

```
IF_PARAMS = {"Vthr": 5.0}
```

```
TIMESTEP = 1.0
```

```
PRESENT_TIMESTEPS = 100
```

```
INPUT_CURRENT_SCALE = 1.0 / 100.0
```

Input required for neurons to spike

How long to present each digit

How to scale image intensity to  
input currents

```
# -----  
# Custom GeNN models  
# -----  
# Very simple integrate-and-fire neuron model  
if_model = create_custom_neuron_class(  
    "if_model",  
    param_names=["Vthr"],  
    var_name_types=[("V", "scalar"), ("SpikeCount", "unsigned int")],  
    sim_code="$$(V) += $(Isyn) * DT;",  
    reset_code=""  
    $(V) = 0.0;  
    $(SpikeCount)++;  
    """,  
    threshold_condition_code="$$(V) >= $(Vthr)")
```

Internal name of model -  
must be unique

```
# -----  
# Custom GeNN models  
# -----  
# Very simple integrate-and-fire neuron model  
if_model = create_custom_neuron_class(  
    "if_model",  
    param_names=["Vthr"],  
    var_name_types=[("V", "scalar"), ("SpikeCount", "unsigned int")],  
    sim_code="$$(V) += $(Isyn) * DT;",  
    reset_code=""  
    $(V) = 0.0;  
    $(SpikeCount)++;  
    """,  
    threshold_condition_code="$$(V) >= $(Vthr)"
```

Parameters are common across all neurons in population (layer)

State variables used to track per-neuron membrane voltage and spike count

```

# -----
# Custom GeNN models
# -----
# Very simple integrate-and-fire neuron model
if_model = create_custom_neuron_class(
    "if_model",
    param_names=["Vthr"],
    var_name_types=[("V", "scalar"), ("SpikeCount", "unsigned int")],
    sim_code="$$(V) += $(Isyn) * DT;",
    reset_code="",
    $$(V) = 0.0;
    $(SpikeCount)++;
    "",
    threshold_condition_code="$$(V) >= $(Vthr)"
)

```

Parameters are common across all neurons in population (layer)

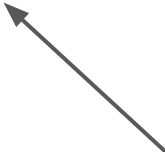
Neuron simply integrates input current  $$(Isyn)$  every timestep

```
# -----  
# Custom GeNN models  
# -----  
# Very simple integrate-and-fire neuron model  
if_model = create_custom_neuron_class(  
    "if_model",  
    param_names=["Vthr"],  
    var_name_types=[("V", "scalar"), ("SpikeCount", "unsigned int")],  
    sim_code="$$(V) += $(Isyn) * DT;",  
    reset_code=""  
    $$(V) = 0.0;  
    $$(SpikeCount)++;  
    "",  
    threshold_condition_code="$$(V) >= $(Vthr)")
```

When neuron spikes,  $$(V)$  is reset  
and  $$(SpikeCount)$  is incremented

Neuron spikes when  $$(V)$  goes  
above  $$(Vthr)$


```
# -----  
# Custom GeNN models  
# -----  
# Very simple integrate-and-fire neuron model  
if_model = create_custom_neuron_class(  
    "if_model",  
    param_names=["Vthr"],  
    var_name_types=[("V", "scalar"), ("SpikeCount", "unsigned int")],  
    sim_code="$ (V) += $(Isyn) * DT;",  
    reset_code=""  
    $(V) = 0.0;  
    $(SpikeCount)++;  
    """,  
    threshold_condition_code="$ (V) >= $(Vthr)")  
  
# Current source model which injects current with a magnitude specified by a state variable  
cs_model = create_custom_current_source_class(  
    "cs_model",  
    var_name_types=[("magnitude", "scalar")],  
    injection_code="$ (injectCurrent, $(magnitude));")
```



Current source 'injects' current  
specified by state variable each  
timestep


```
# -----  
# Build model  
# -----  
# Create GeNN model  
model = GeNNModel("float", "tutorial_1")  
model.dT = TIMESTEP  
  
# Load weights  
weights = []  
while True:  
    filename = "weights_%u_%u.npy" % (len(weights), len(weights) + 1)  
    if path.exists(filename):  
        weights.append(np.load(filename))  
    else:  
        break
```

Create new network using single-precision by default and generating code into tutorial\_1 directory




```
# -----  
# Build model  
# -----  
# Create GeNN model  
model = GeNNModel("float", "tutorial_1")  
model.dT = TIMESTEP  
  
# Load weights  
weights = []  
while True:  
    filename = "weights_%u_%u.npy" % (len(weights), len(weights) + 1)  
    if path.exists(filename):  
        weights.append(np.load(filename))  
    else:  
        break
```

Set simulation time-step  
(somewhat arbitrary with artificial  
models)



Load any weights present in  
directory into list





```

# -----
# Build model
# -----
# Create GeNN model
model = GeNNModel("float", "spiking_eval")
model.dT = TIMESTEP

# Load weights
weights = []
while True:
    filename = "weights_%u_%u.npy" % (len(weights), len(weights) + 1)
    if path.exists(filename):
        weights.append(np.load(filename))
    else:
        break

# Initial values to initialise all neurons
if_init = {"V": 0.0, "SpikeCount":0}

# Create first neuron layer
neuron_layers = [model.add_neuron_population("neuron0", weights[0].shape[0],
                                             if_model, IF_PARAMS, if_init)]

# Create subsequent neuron layer
for i, w in enumerate(weights):
    neuron_layers.append(model

```

Initial values for all IF neurons

Create neuron population with a neuron for each of the first layer's input dimensions

```

# -----
# Build model
# -----
# Create GeNN model
model = GeNNModel("float", "spiking_eval")
model.dT = TIMESTEP

# Load weights
weights = []
while True:
    filename = "weights_%u_%u.npy" % (len(weights), len(weights) + 1)
    if path.exists(filename):
        weights.append(np.load(filename))
    else:
        break

# Initial values to initialise all neurons to
if_init = {"V": 0.0, "SpikeCount":0}

# Create first neuron layer
neuron_layers = [model.add_neuron_population("neuron0", weights[0].shape[0],
                                             if_model, IF_PARAMS, if_init)]

# Create subsequent neuron layer
for i, w in enumerate(weights):
    neuron_layers.append(model.add_neuron_population("neuron%u" % (i + 1),
                                                    w.shape[1], if_model,
                                                    IF_PARAMS, if_init))

```

Create neuron populations matching subsequent layer's output dimensions

```
# Create synaptic connections between layers
for i, (pre, post, w) in enumerate(zip(neuron_layers[:-1], neuron_layers[1:], weights)):
    model.add_synapse_population(
        "synapse%u" % i, "DENSE_INDIVIDUALG", NO_DELAY,
        pre, post,
        "StaticPulse", {}, {"g": w.flatten()}, {}, {},
        "DeltaCurr", {}, {})
```

No synaptic delays

Name of  
synapse  
population

Dense matrix with individual  
state variables (weights) for  
each synapse

<http://genn-team.github.io/genn/documentation/4/html/d5/d39/subsect34.html>

```
# Create synaptic connections between layers
for i, (pre, post, w) in enumerate(zip(neuron_layers[:-1], neuron_layers[1:], weights)):
    model.add_synapse_population(
        "synapse%u" % i, "DENSE_INDIVIDUALG", NO_DELAY,
        pre, post,
        "StaticPulse", {}, {"g": w.flatten()}, {}, {},
        "DeltaCurr", {}, {})
```

**Source**  
population

**Target**  
population

```
# Create synaptic connections between layers
for i, (pre, post, w) in enumerate(zip(neuron_layers[:-1], neuron_layers[1:], weights)):
    model.add_synapse_population(
        "synapse%u" % i, "DENSE_INDIVIDUALG", NO_DELAY,
        pre, post,
        "StaticPulse", {}, {"g": w.flatten()}, {}, {},
        "DeltaCurr", {}, {})
```

Static synapses  
have no parameters

Use built-in static  
synapse model

Initialise the weight of  
each synapse to the  
pre-trained weights

```
# Create synaptic connections between layers
for i, (pre, post, w) in enumerate(zip(neuron_layers[:-1], neuron_layers[1:], weights)):
    model.add_synapse_population(
        "synapse%u" % i, "DENSE_INDIVIDUALG", NO_DELAY,
        pre, post,
        "StaticPulse", {}, {"g": w.flatten()}, {}, {},
        "DeltaCurr" {}, {})
```

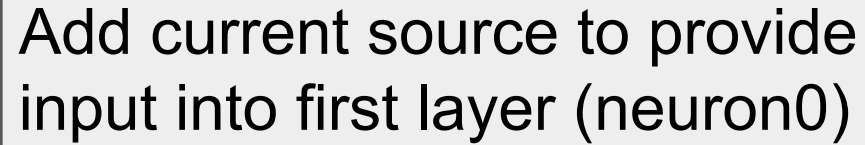
Use built-in delta postsynaptic model

This model has no parameters or variables



```
# Create synaptic connections between layers
for i, (pre, post, w) in enumerate(zip(neuron_layers[:-1], neuron_layers[1:], weights)):
    model.add_synapse_population(
        "synapse%u" % i, "DENSE_INDIVI
        pre, post,
        "StaticPulse", {}, {"g": w.flat
        "DeltaCurr", {}, {})
```

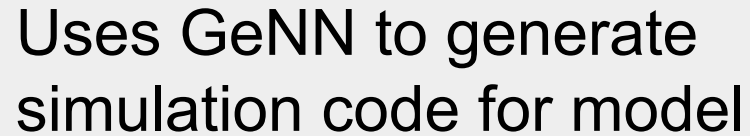
Add current source to provide input into first layer (neuron0)



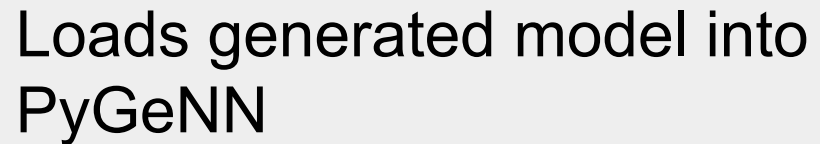
```
# Create current source to deliver input to first layers of neurons
current_input = model.add_current_source("current_input", cs_model,
                                         "neuron0", {}, {"magnitude": 0.0})
```

```
# Build and load our model
model.build()
model.load()
```

Uses GeNN to generate simulation code for model



Loads generated model into PyGeNN



```
# -----  
# Simulate  
# -----  
# Load testing data  
testing_images = np.load("testing_images.npy")  
testing_labels = np.load("testing_labels.npy")  
  
# Check dimensions match network  
assert testing_images.shape[1] == weights[0].shape[0]  
assert np.max(testing_labels) == (weights[1].shape[1] - 1)  
  
# Set current input by scaling first image  
current_input.vars["magnitude"].view[:] = testing_images[0] * INPUT_CURRENT_SCALE
```

Load MNIST data



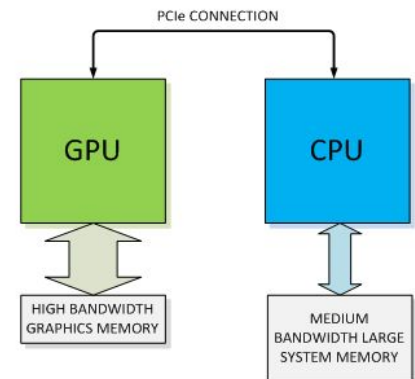
Copy first image into memory view of current source magnitude





```
# -----  
# Simulate  
# -----  
# Load testing data  
testing_images = np.load("testing_images.npy")  
testing_labels = np.load("testing_labels.npy")  
  
# Check dimensions match network  
assert testing_images.shape[1] == weights[0].shape[0]  
assert np.max(testing_labels) == (weights[1].shape[1] - 1)  
  
# Set current input by scaling first image  
current_input.vars["magnitude"].view[:] = testing_images[0] * INPUT_CURRENT_SCALE  
  
# Upload  
current_input.push_var_to_device("magnitude")
```

Upload this variable to GPU



```
# Simulate
layer_spikes = [[] for _ in enumerate(neuron_layers)]
while model.timestep < PRESENT_TIMESTEPS:
    # Advance simulation
    model.step_time()

    # Loop through neuron layers
    for i, l in enumerate(neuron_layers):
        # Download spikes
        l.pull_current_spikes_from_device()

        # Add to data structure
        layer_spikes[i].append(np.copy(l.current_spikes))
```

Advance simulation

Download spikes  
emitted this timestep  
from GPU

Add spikes to data  
structure

Time [ms]	0	0	1	1	2
Neuron index	1	14	13	100	56

```

# -----
# Plotting
# -----
import matplotlib.pyplot as plt

# Create a plot with axes for each
fig, axes = plt.subplots(len(neuron_layers), sharex=True)

# Loop through axes and their corresponding neuron populations
for a, s, l in zip(axes, layer_spikes, neuron_layers):
    spike_ids = np.concatenate(spks)
    spike_times = np.concatenate([np.ones_like(s) * i * TIMESTEP
                                   for i, s in enumerate(spks)])

    # Plot spikes
    a.scatter(spike_times, spike_ids, s=1)

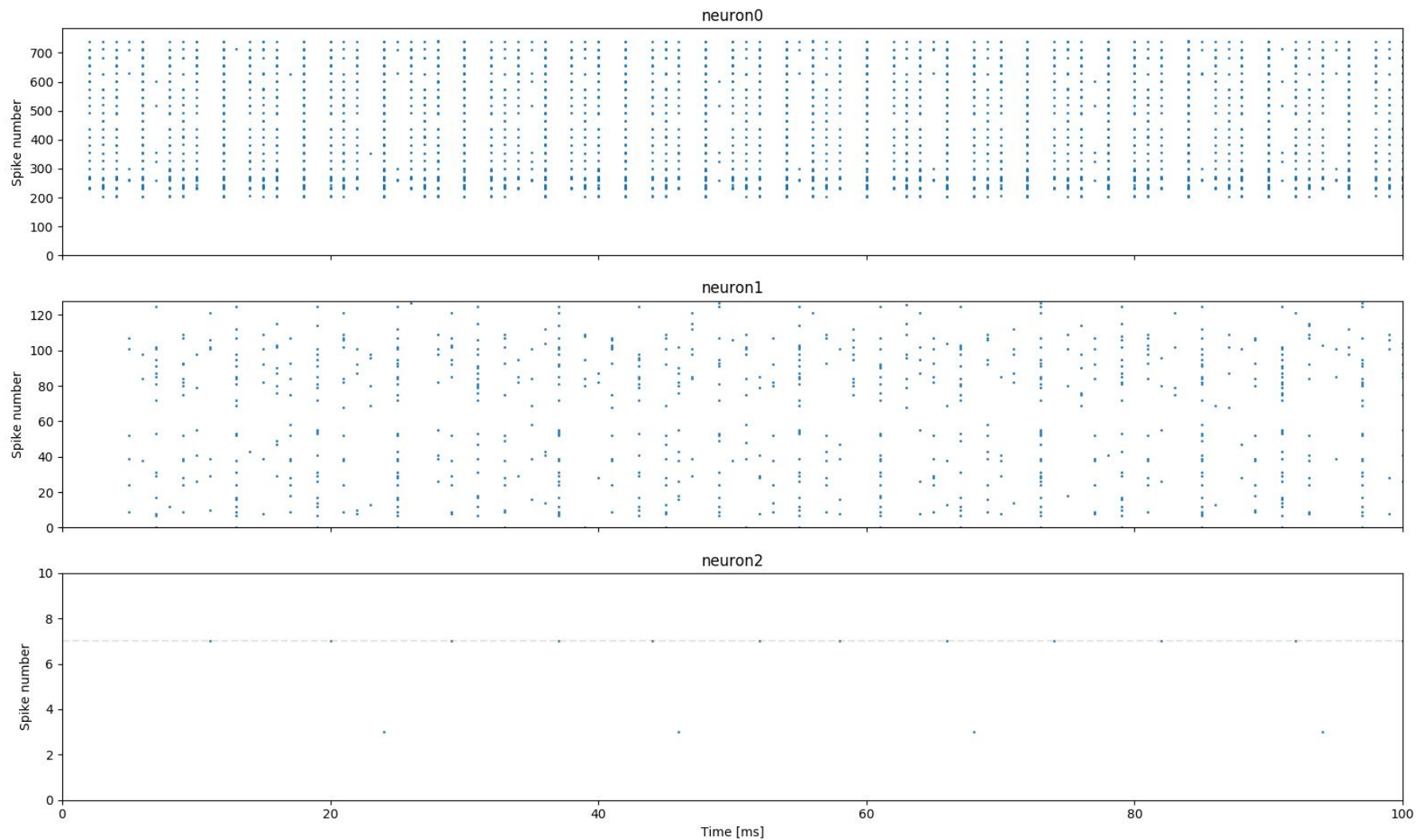
    # Set title, axis labels
    a.set_title(l.name)
    a.set_ylabel("Spike number")
    a.set_xlim((0, PRESENT_TIMESTEPS * TIMESTEP))
    a.set_ylim((0, l.size))

# Add an x-axis label and translucent line showing the correct label
axes[-1].set_xlabel("Time [ms]")
axes[-1].hlines(testing_labels[0], xmin=0, xmax=PRESENT_TIMESTEPS,
                linestyle="--", color="gray", alpha=0.2)

# Show plot
plt.show()

```

# Results



## Part 2: Evaluating entire dataset

1. Presenting entire MNIST testing set to network
2. Calculating inference performance

```
# -----  
# Simulate  
# -----  
# Load testing data  
testing_images = np.load("testing_images.npy")  
testing_labels = np.load("testing_labels.npy")  
  
# Check dimensions match network  
assert testing_images.shape[1] == weights[0].shape[0]  
assert np.max(testing_labels) == (weights[1].shape[1] - 1)  
  
# Get views to efficiently access state variables  
current_input_magnitude = current_input.vars["magnitude"].view  
output_spike_count = neuron_layers[-1].vars["SpikeCount"].view  
layer_voltages = [l.vars["V"].view for l in neuron_layers]
```



Cache memory views of required state variables

```

# Simulate
num_correct = 0
while model.timestep < (PRESENT_TIMESTEPS * testing_images.shape[0]):
    # Calculate the timestep within the presentation
    timestep_in_example = model.timestep % PRESENT_TIMESTEPS
    example = int(model.timestep // PRESENT_TIMESTEPS)

    # If this is the first timestep of presenting the example
    if timestep_in_example == 0:
        current_input_magnitude[:] = testing_images[example]
        current_input.push_var_to_device("magnitude")

    # Loop through all layers and their corresponding voltage views
    for l, v in zip(neuron_layers, layer_voltages):
        # Manually 'reset' voltage
        v[:] = 0.0


        # Upload
        l.push_var_to_device("V")

    # Zero spike count
    output_spike_count[:] = 0
    neuron_layers[-1].push_var_to_device("SpikeCount")

# Advance simulation
model.step_time()

```

Divide timestep into  
example index and  
timestep within  
example



```
# Simulate
```

```
num_correct = 0
```


```
while model.timestep < (PRESENT_TIMESTEPS * testing_images.shape[0]):
```

```
    # Calculate the timestep within the presentation
```

```
    timestep_in_example = model.timestep % PRESENT_TIMESTEPS
```

```
    example = int(model.timestep // PRESENT_TIMESTEPS)
```

Copy image into memory  
view and upload to GPU



```
    # If this is the first timestep of presenting the example
```

```
    if timestep_in_example == 0:
```

```
        current_input_magnitude[:] = testing_images[example] * INPUT_CURRENT_SCALE
```

```
        current_input.push_var_to_device("magnitude")
```

```
    # Loop through all layers and their corresponding voltage views
```

```
    for l, v in zip(neuron_layers, layer_voltages):
```

```
        # Manually 'reset' voltage
```

```
        v[:] = 0.0
```

Set all neuron voltages to zero



```
        # Upload
```

```
        l.push_var_to_device("V")
```

Upload to GPU



```
    # Zero spike count
```

```
    output_spike_count[:] = 0
```

```
    neuron_layers[-1].push_var_to_device("SpikeCount")
```

```
# Advance simulation
```

```
model.step_time()
```



```

# Simulate
num_correct = 0
while model.timestep < (PRESENT_TIMESTEPS * testing_images.shape[0]):
    # Calculate the timestep within the presentation
    timestep_in_example = model.timestep % PRESENT_TIMESTEPS
    example = int(model.timestep // PRESENT_TIMESTEPS)

    # If this is the first timestep of presenting the example
    if timestep_in_example == 0:
        current_input_magnitude[:] = testing_images[example] * INPUT_CURRENT_SCALE
        current_input.push_var_to_device("magnitude")

        # Loop through all layers and their corresponding voltage views
        for l, v in zip(neuron_layers, layer_voltages):
            # Manually 'reset' voltage
            v[:] = 0.0

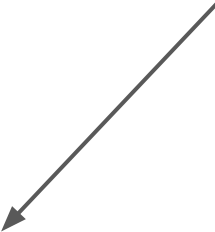
            # Upload
            l.push_var_to_device("V")

        # Zero spike count
        output_spike_count[:] = 0
        neuron_layers[-1].push_var_to_device("SpikeCount")

    # Advance simulation
    model.step_time()

```

Zero spike count for all  
output layer neurons  
and upload to GPU



Advance simulation



```
# If this is the LAST timestep of presenting the example
```

```
if timestep_in_example == (PRESENT_TIMESTEPS - 1):
```

```
    # Download spike count from last layer
```

```
    neuron_layers[-1].pull_var_from_device("SpikeCount")
```

```
    # Find which neuron spiked the most to get prediction
```

```
    predicted_label = np.argmax(output_spike_count)
```

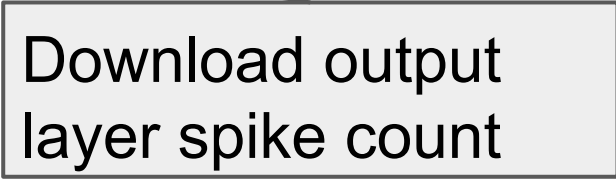
```
    true_label = testing_labels[example]
```

```
    print("\tExample=%u, true label=%u, predicted label=%u" % (example,
                                                                true_label,
                                                                predicted_label))
```

```
    if predicted_label == true_label:
```

```
        num_correct += 1
```

```
print("Accuracy %f%%" % ((num_correct / float(testing_images.shape[0])) * 100.0))
```



Download output  
layer spike count

# Results

```
Example=9965, true label=3, predicted label=3
Example=9966, true label=6, predicted label=6
Example=9967, true label=8, predicted label=8
Example=9968, true label=7, predicted label=7
Example=9969, true label=1, predicted label=1
Example=9970, true label=5, predicted label=5
Example=9971, true label=2, predicted label=2
Example=9972, true label=4, predicted label=4
Example=9973, true label=9, predicted label=9
Example=9974, true label=4, predicted label=4
Example=9975, true label=3, predicted label=3
Example=9976, true label=6, predicted label=6
Example=9977, true label=4, predicted label=4
Example=9978, true label=1, predicted label=1
Example=9979, true label=7, predicted label=7
Example=9980, true label=2, predicted label=2
Example=9981, true label=6, predicted label=6
Example=9982, true label=5, predicted label=5
Example=9983, true label=0, predicted label=0
Example=9984, true label=1, predicted label=1
Example=9985, true label=2, predicted label=2
Example=9986, true label=3, predicted label=3
Example=9987, true label=4, predicted label=4
Example=9988, true label=5, predicted label=5
Example=9989, true label=6, predicted label=6
Example=9990, true label=7, predicted label=7
Example=9991, true label=8, predicted label=8
Example=9992, true label=9, predicted label=9
Example=9993, true label=0, predicted label=0
Example=9994, true label=1, predicted label=1
Example=9995, true label=2, predicted label=2
Example=9996, true label=3, predicted label=3
Example=9997, true label=4, predicted label=4
Example=9998, true label=5, predicted label=5
Example=9999, true label=6, predicted label=6
```

Accuracy 97.440000%

(tensorflow) jk421@inf900801:~/offline\_train\_examples\$

## Part 3: Play time!

- How does `PRESENT_TIMESTEPS` affect performance?
- Can you reduce the number of spikes while maintaining performance by modifying `IF_PARAMS` and `INPUT_CURRENT_SCALE`?
- Try training your own sequential model with dense layers, save the weights and see how this code performs

Thank you!

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