Spike-based machine learning with GeNN

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Brains on Board

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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

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

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. Install python module with setuptools using:
   ```
   python setup.py develop
   ```

Installation from source on Windows

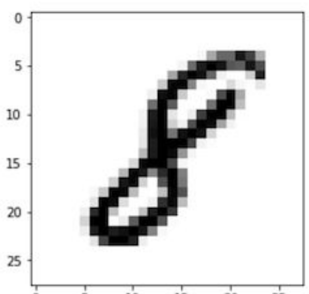
1. Download latest release of GeNN from
   https://github.com/genn-team/genn/releases
2. Ensure that you have at least Python 3.5 and Visual Studio 2015 installed as well as swig
3. Ensure that your command prompt has Python and Visual studio properly configured i.e. by activating conda within a Visual Studio "x64 Native Tools Command Prompt"
4. From GeNN directory, build as a dynamic library using:
   `msbuild genn.sln /t:Build /p:Configuration=Release_DLL`
5. Copy the newly built DLLs into pygenn using
   `copy /Y lib\genn*Release_DLL.* pygenn\genn_wrapper`
6. Install python module with setuptools using:
   `python setup.py develop`

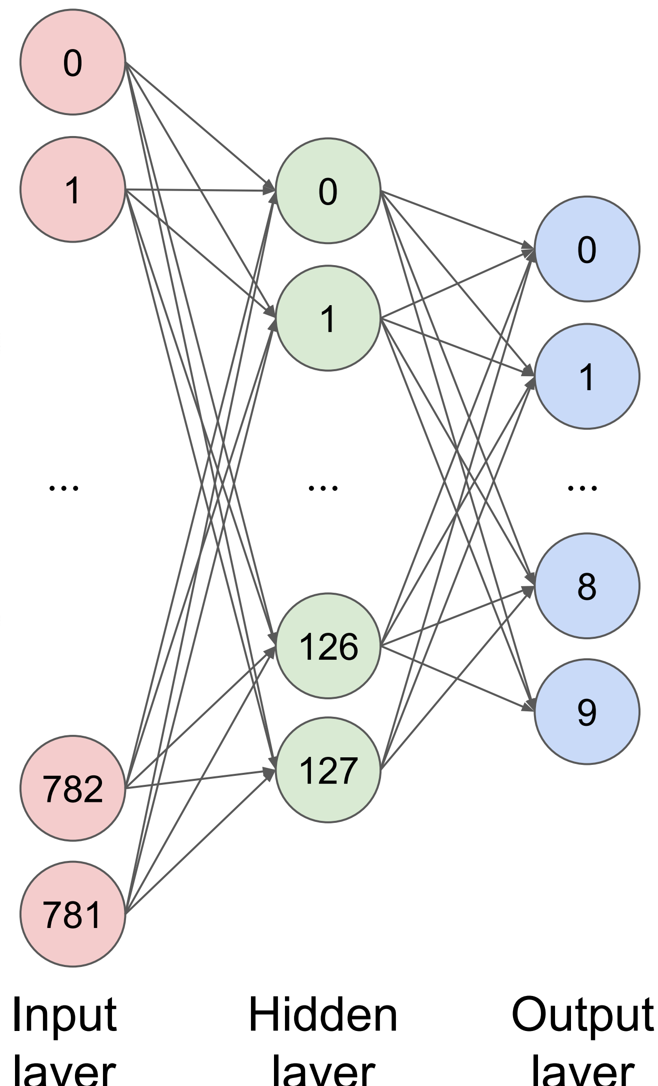
Tutorial repository

- Checkout from:
  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

```python
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 standard Python packages

Import some useful PyGeNN components

```python
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

```python
# ----------------------------------------------------------------------------
# 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

```python
# ------------------------------------------------------------------------------
# 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

```python
# -----------------------------------------------------------------------------
# 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)

```python
# ------------------------------------------------------------------------------
# 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

```python
# ----------------------------------------------------------------------------
# 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

```python
# ----------------------------------------------------------------------------
# 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 artifical 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 f
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

```python
# --------------------------------------------------------------------------
# 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

```python
# 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.fla
        "DeltaCurr", {}, {})

# 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()
```

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

Uses GeNN to generate simulation code for model

Loads generated model into PyGeNN

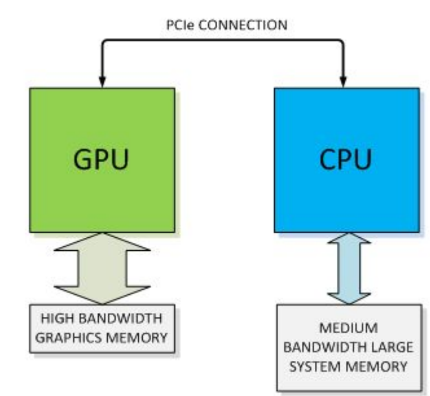
```python
# ----------------------------------------------------------------------------
# Simulate
# ----------------------------------------------------------------------------
# Load testing data
testing_images = np.load("testing_images.npy")
testing_labels = np.load("testing_labels.npy")

# 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

```python
# ----------------------------------------------------------------------------
# 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
model.push_var_to_device("current_input", "magnitude")
```

Upload this variable to GPU



```python
# Simulate
layer_spikes = [(np.empty(0), np.empty(0)) 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
        model.pull_current_spikes_from_device(l.name)

        # Add to data structure
        spike_times = np.ones_like(l.current_spikes) * model.t
        layer_spikes[i] = (np.hstack((layer_spikes[i][0], l.current_spikes)),
                           np.hstack((layer_spikes[i][1], spike_times)))
```

Advance simulation

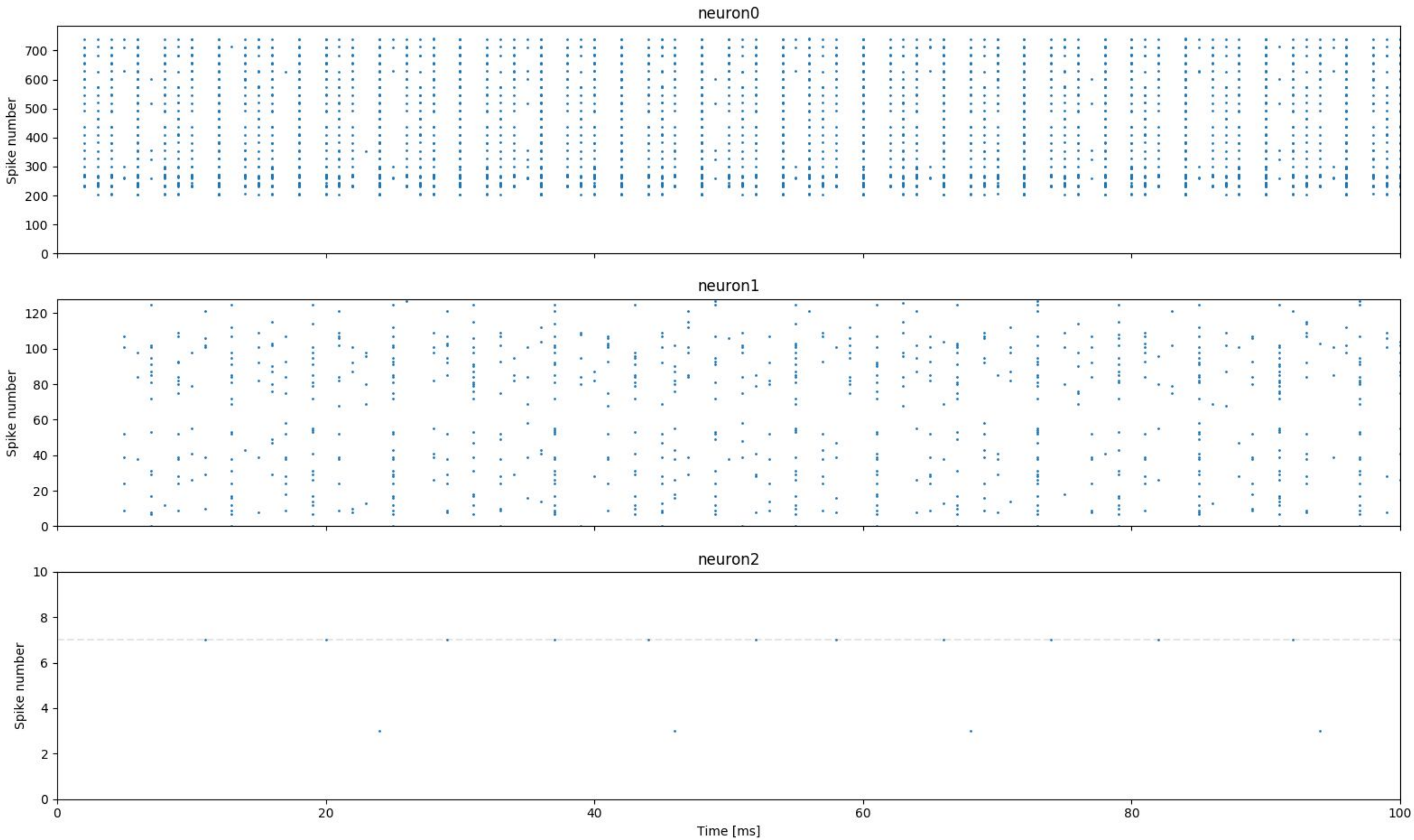
Download spikes emitted this timestep from GPU

Add spikes to data structure

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

```python
# -----------------------------------------------------------------------------
# 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):
    # Plot spikes
    a.scatter(s[1], s[0], 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



neuron0
Spike number
700
600
500
400
300
200
100
0
neuron1
Spike number
120
100
80
60
40
20
0
neuron2
Spike number
10
8
6
4
2
0
0
20
40
60
80
100
Time [ms]

Part 2: Evaluating entire dataset

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

```python
# ----------------------------------------------------------------------------
# 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

```python
# 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]
        model.push_var_to_device("current_input", "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
            model.push_var_to_device(l.name, "V")

        # Zero spike count
        output_spike_count[:] = 0
        model.push_var_to_device(neuron_layers[-1].name, "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 presentati
    timestep_in_example = model.timestep % PRESENT_
    example = int(model.timestep // PRESENT_TIMEST

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

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

    # Advance simulation
    model.step_time()
```

Copy image into memory view and upload to GPU

Set all neuron voltages to zero

Upload to GPU

```python
# 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
        model.push_var_to_device("current_input", "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
            model.push_var_to_device(l.name, "V")

        # Zero spike count
        output_spike_count[:] = 0
        model.push_var_to_device(neuron_layers[-1].name, "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
        model.pull_var_from_device(neuron_layers[-1].name, "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_example$
```

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!

J.C.Knight@sussex.ac.uk