# Creating New Neuron Models for SpiNNaker

## Introduction

This manual will guide you in the creation of new neuron models to be run on SpiNNaker. This includes the C code that will be compiled to run on the SpiNNaker hardware, as well as the Python code which interacts with the PyNN script to configure the model.

## Installation

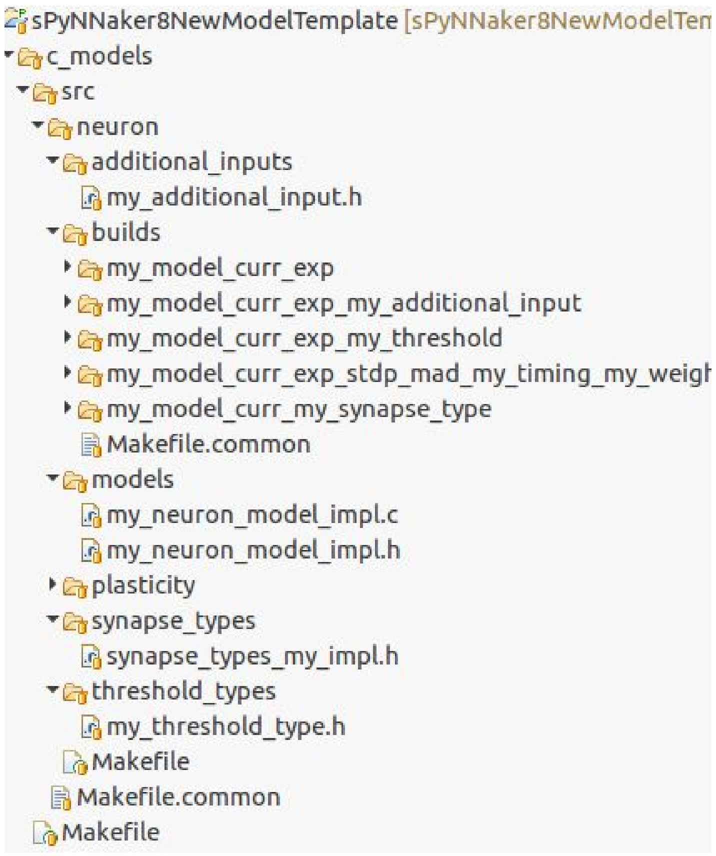
In order to create new models, you will need to ensure that you have set up a development environment suitable for compiling C code for SpiNNaker. This can be done by following the instructions here:

http://spinnakermanchester.github.io/spynnaker/4.0.0/PyNNonSpiNNakerExtensions.html

## Project Layout

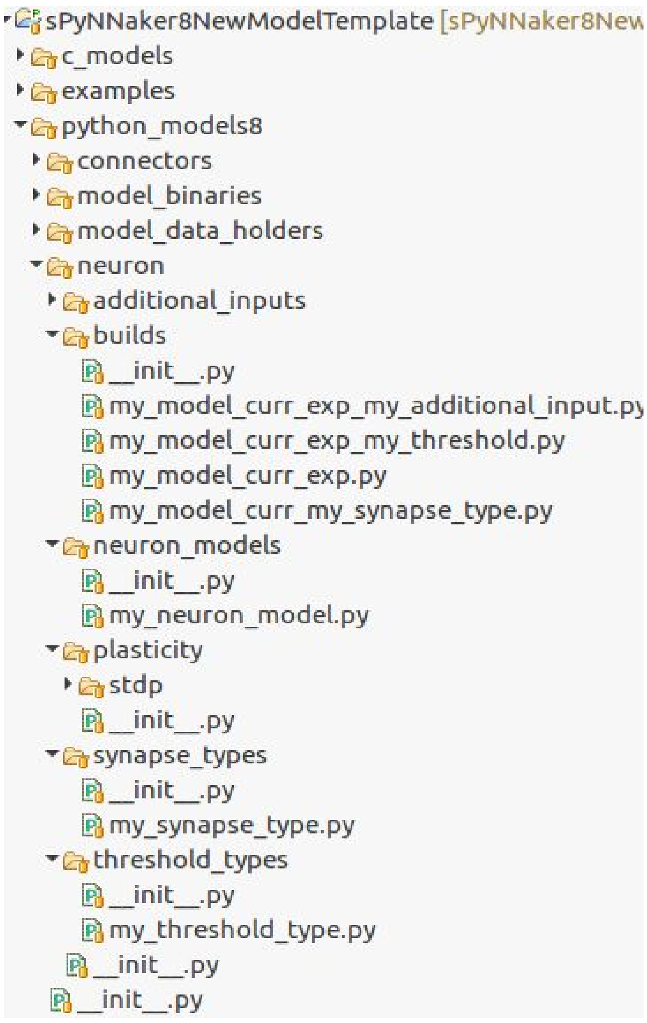
The recommended layout for a new model project is shown below; this example shows a model called “my_model”, with current-based exponential synapses. It is recommended that the C and Python code is kept in the same project to help keep them synchronized.

**C code**



```
sPyNNaker8NewModelTemplate [sPyNNaker8NewModelTem
▾ c_models
  ▾ src
    ▾ neuron
      ▾ additional_inputs
          my_additional_input.h
      ▾ builds
        ▸ my_model_curr_exp
        ▸ my_model_curr_exp_my_additional_input
        ▸ my_model_curr_exp_my_threshold
        ▸ my_model_curr_exp_stdp_mad_my_timing_my_weigh
        ▸ my_model_curr_my_synapse_type
          Makefile.common
      ▾ models
          my_neuron_model_impl.c
          my_neuron_model_impl.h
      ▸ plasticity
      ▾ synapse_types
          synapse_types_my_impl.h
      ▾ threshold_types
          my_threshold_type.h
        Makefile
      Makefile.common
    Makefile
```

**Python code**



```
sPyNNaker8NewModelTemplate [sPyNNaker8New
▸ c_models
▸ examples
▾ python_models8
  ▸ connectors
  ▸ model_binaries
  ▸ model_data_holders
  ▾ neuron
    ▸ additional_inputs
    ▾ builds
        __init__.py
        my_model_curr_exp_my_additional_input.py
        my_model_curr_exp_my_threshold.py
        my_model_curr_exp.py
        my_model_curr_my_synapse_type.py
    ▾ neuron_models
        __init__.py
        my_neuron_model.py
    ▾ plasticity
      ▸ stdp
        __init__.py
    ▾ synapse_types
        __init__.py
        my_synapse_type.py
    ▾ threshold_types
        __init__.py
        my_threshold_type.py
      __init__.py
    __init__.py
```

For SpiNNaker 4.0.0, this template structure can be downloaded from one of the following locations:
https://spinnakermanchester.github.io/latest/spynnaker_new_model_template_zip.html
https://spinnakermanchester.github.io/latest/spynnaker_new_model_template_tar_gz.html

If you have already set up a development environment for SpiNNaker in C and Python following the instructions at https://spinnakermanchester.github.io/development/devenv.html then this template structure can be downloaded from https://github.com/SpiNNakerManchester/sPyNNaker8NewModelTemplate.git (for PyNN 0.8) or from https://github.com/SpiNNakerManchester/sPyNNaker7NewModelTemplate.git (for PyNN 0.7).

## C model builds

All neuron builds consist of a collection of components which when connected together produce a complete neural model. These components are defined in **Table 1**.

| **Component** | **Definition** |
|---|---|
| Input component | The type of input the model takes. Currently there are conductance and current based inputs supported by sPyNNaker. It is possible to define other input types, but this is not described in this tutorial. |
| Synapse type component | The synapse type controls the shaping of the synapses in response to the input weights. Within sPyNNaker, support so far includes exponential synapses (with one excitatory and one inhibitory synapse per neuron which decay exponentially with a configured time-constant) and dual-excitatory exponential synapses (with 2 separate excitatory synapses and one inhibitory synapse per neuron, decaying as per the previous type). |
| Threshold component | Determines the threshold of the membrane voltage which determines when the neuron spikes. Currently the only implementations are a static threshold and a stochastic Maass threshold. |
| Additional input component | Any additional input current that might be based on the membrane voltage or other parameters. |
| Neuron model component | Determines how the neuron state changes over time and the outputs the current membrane voltage of the neuron. Currently there are Izhikevich (IZK) and Leaky-Integrate-and-Fire (LIF) implementations supported by sPyNNaker. |
| Synapse dynamics component | Determines how plasticity works within the model. sPyNNaker implements a model for no plasticity (i.e. static dynamics), and two different STDP dynamics models. Only static dynamics are considered in this tutorial. |

**Table 1: Different supported components**

Each build is stored within its own folder in the `c_models->src->neuron->builds` directory. Within each build is a *Makefile* containing the separate components required to build that specific form of neuron model.

If we look at the simple my_model_curr_exp's Makefile located in:

`c_models->src->neuron->builds->my_model_curr_exp->Makefile`

we can see the lines shown in **Code 1**.

```
APP = $(notdir $(CURDIR))
BUILD_DIR = build/

NEURON_MODEL = $(EXTRA_SRC_DIR)/neuron/models/my_neuron_model_impl.c
NEURON_MODEL_H = $(EXTRA_SRC_DIR)/neuron/models/my_neuron_model_impl.h
INPUT_TYPE_H = $(SOURCE_DIR)/neuron/input_types/input_type_current.h
THRESHOLD_TYPE_H = $(SOURCE_DIR)/neuron/threshold_types/threshold_type_static.h
SYNAPSE_TYPE_H = $(SOURCE_DIR)/neuron/synapse_types/synapse_types_exponential_impl.h
SYNAPSE_DYNAMICS = $(SOURCE_DIR)/neuron/plasticity/synapse_dynamics_static_impl.c

```

11. include ../Makefile.common

**Code 1: my_model_curr_exp's Makefile**

- Line 1 declares the name of the APP - here we are using the name of the current directory. (The aplx extension is added automatically.)
- Line 2 declares the directory in which the model will be built. This is where object files and other intermediate files are stored; the final aplx location is determined in Makefile.common (see later).
- Lines 4 and 5 are the files that make up the neuron model component (described in **Table 1**) used for this model build (both the .c and .h files are needed). Note that these are stated to be in the $(EXTRA_SRC_DIR) folder - this is declared to be the c_models/src folder within the archive within Makefile.common. The sPyNNaker standard source files are declared to be within $(SOURCE_DIR), and these are used by other components.
- Line 6 states the input type component (described in **Table 1**) for this model. Input types are implemented entirely in a header file.
- Line 7 states the threshold type component (described in **Table 1**) for this model. Threshold types are implemented entirely in a header file.
- Line 8 states the synapse type component (described in **Table 1**) for this model. Synapse types are implemented entirely in a header file.
- Line 9 states the synapse dynamics component (described in **Table 1)** for this model.
- Line 11 tells the make system to import the next level up Makefile so that it can detect where the rest of the code needed to be linked in can be found.

Other Makefile instances might also include TIMING_DEPENDENCE_H and WEIGHT_DEPENDENCE_H; these are used when the synapse dynamics includes plasticity. A tutorial on how to add new plasticity implementations is covered here.

To make a new neuron model build, you must either:

1. Create a copy of the example builds discussed above,
2. Modify the names and component listings,
3. Mody Line 1 of the Makefile located in `src->neuron->Makefile` so that it includes your new build.

Or:

1. Change the template's component listings directly.

## Compiling a new model

As the build relies on header files that are not explicitly specified in the Makefile, some of the changes that you make may require you to clean the build beforehand, by running

```
make clean
```

Once the Makefile has been edited appropriately, you can build the binary by simply changing to the directory containing the Makefile and typing:

```
make
```

Assuming this builds with no errors, you should find the aplx files have been built and placed into the python_models8->model_binaries directory (as specified by Makefile.common) in the Python code.

Finally, you can also build the application in debug mode by typing:

```
make SPYNNAKER_DEBUG=DEBUG
```

This will enable the log_debug statements in the code, which print out information to the iobuf buffers on the SpiNNaker machine. By default, the tools won't extract the printed error messages. To enable this behaviour, you can add the following to your local .spynnaker.cfg file:

```
[Reports]
extract_iobuf=True
```

The "iobuf" messages will then be downloaded after the execution is complete. These are stored relative to your executing script in reports/DATE-TIME-ID/run_N/provenance_data/ for appropriate values of DATE, TIME, ID and N; each is a .txt file containing any output printed from each core used during the execution of your program.

## C code file interfaces

This section goes through each interface for the different components of the neuron build and explains what each one does.

### Neuron Models

The C header file defines:

- The neuron data structure `neuron_t`. This includes the parameters and state for each neuron to be executed on a core. This commonly includes the membrane voltage of the neuron, as well as an offset input current.
- The global parameters data structure `global_neuron_params_t`. This includes parameters that are shared across all neurons within a population. This might include such things as the time step of the simulation.

See `neuron_model_my_model_curr_exp.h` in the template for an example of a header file. Comments show where the file should be updated to create your own model.

The C code file defines the functions that make up the interface of the neuron API. Note that pointer types are automatically created for the data structures defined in the header as follows:

```
neuron_t * → neuron_pointer_t
global_neuron_params_t * → global_neuron_params_pointer_t
```

-
  ```
  void neuron_model_set_global_neuron_params(
        global_neuron_params_pointer_t params)
  ```
  This function is used to set the global parameters after they have been read by the initialization function. This would often be used to store the parameters in a static variable for later use.

-
  ```
  state_t neuron_model_state_update(
        input_t exc_input, input_t inh_input,
        input_t external_bias, neuron_pointer_t neuron)
  ```
  This function takes the excitatory and inhibitory input, any external bias input (used in some plasticity models), and a neuron data structure and uses these to compute the new state of the given neuron at this timestep. This function is where any differential equation solving should be implemented. After the state update, the function should return the value of the membrane voltage. Note that the input will always be presented as current - conductance input is converted to current input in the input type. Additionally, the input values are all positive, including the inhibitory input; thus if the total input current is being considered, the inhibitory input current should be subtracted from the excitatory input current.

- `state_t neuron_model_get_membrane_voltage(neuron_pointer_t neuron)`
  This function should return the membrane voltage of the neuron from the given neuron structure. This may simply return the value of a variable in the structure, or it might perform a more complex calculation to obtain the membrane voltage. The value returned is used for the recording of the membrane voltage in the simulation, and is taken before the state update is performed.

- `void neuron_model_has_spiked(neuron_pointer_t neuron);`
  This function is used to reset the parameters of the neuron after it has spiked. It is called only if the membrane voltage value returned from `neuron_model_state_update` is determined to be above the threshold determined by the threshold type.

- `void neuron_model_print_state_variables(restrict neuron_pointer_t neuron)`
  This function is only used when the neuron model is compiled in "debug" mode. It should use the "log_debug" function to print each of the state variables of the neuron that change during a run and that might be useful in debugging.

- `void neuron_model_print_parameters(restrict neuron_pointer_t neuron)`
  This function is only used when the neuron model is compiled in "debug" mode. It should use the "log_debug" function to print each of the parameters of the neuron that don't change during a run and that might be useful in debugging.

See `neuron_model_my_impl.c` in the template for an example of an implementation of the neuron interface.

A number of other modules are available for use for performing mathematical functions as part of the neuron state update. The `spinn_common` library provides a number of efficient fixed-point implementations of common mathematical and probabilistic functions. This includes `random.h`, which provides random number generation, `normal.h`, which provides normal distributions, `exp.h`, which provides an exp function and `log.h` which provides a log function.

## Synapse types

The synapse type header file defines the `synapse_param_t` data structure that determines the parameters required for shaping the synaptic input. For example, this might be done to compensate for the valve behaviour of a synapse in biology (spike goes in, synapse opens, then closes slowly). The parameters for all the synaptic inputs for a single neuron need to be defined in this structure; for example, if there are different parameters for excitatory and inhibitory neurons, both of these parameters must be explicitly defined in this structure. The structure might also contain parameters for computing the initial value that will be added to the input buffer following a spike from a preceding neuron.

Note that the input will have already been delayed by the appropriate amount before it reaches this function, and that the input weights from several spikes may be combined into a single weight. Additionally, the input weights might be either current or conductance as determined by the input type. The synapse type should not perform any conversion of the weights.

The synapse type header file also defines the functions that make up the interface of the synapse type API. The synapse Type API requires the following interface functions to be implemented.

-
  ```
  static void synapse_types_shape_input(
          input_t *input_buffers, index_t neuron_index,
          synapse_param_t* parameters);
  ```
  Shapes the values (current or conductance) in the input buffers for the synapses of a given neuron. The input buffers for all neurons and synapse types are given here, and the following function can be used to obtain the index of the appropriate input buffer given the indices of the neuron and of the

synapse (e.g. if there is an excitatory and inhibitory synapse per neuron, the indices might be 0 and 1 respectively):

```
      index_t synapse_types_get_input_buffer_index(synapse_index, neuron_index)
```

-
  ```
  static void synapse_types_add_neuron_input(
        input_t *input_buffers, index_t synapse_type_index, index_t neuron_index,
        synapse_param_t* parameters, input_t input)
  ```
  Adds a synaptic weight input to the input buffer for a given synapse of a given neuron after a spike has been received (and appropriately delayed). This allows the weight to be scaled as required before it is added to the buffer.

-
  ```
  static input_t synapse_types_get_excitatory_input(
        input_t *input_buffers, index_t neuron_index)
  ```
  Returns the total combined excitatory input from the buffers available for a given neuron id. Note that if several synapses are excitatory, this function should add up the input values (or perform an otherwise appropriate function) to return the total excitatory input value.

-
  ```
  static input_t synapse_types_get_inhibitory_input(
        input_t *input_buffers, index_t neuron_index)
  ```
  Extracts the total combined inhibitory input from the buffers available for a given neuron id. Note that if several synapses are inhibitory, this function should add up the input values (or perform an otherwise appropriate function) to return the total inhibitory input value. Note also that the value should be a positive number; subtraction is performed in the neuron model as required.

- `static const char *synapse_types_get_type_char(index_t synapse_type_index)`
  Returns a human readable character for the type of synapse. Examples would be X = excitatory types and I = inhibitory types.

-
  ```
  static void synapse_types_print_input(
        input_t input_buffers, index_t neuron_index)
  ```
  Prints the input for a neuron id given the available inputs. This is currently only executed when the models are in debug mode.

- `static void synapse_types_print_parameters(synapse_param_t *parameters)`
  Prints the static parameters of the synapse type. This is currently only executed when the models are in debug mode.

See `synapse_types_my_impl.h` for an example of an implementation of a synapse type.

### Threshold types

The threshold type header file defines the `threshold_type_t` data structure that declares the parameters required for the threshold type. This might commonly include the actual threshold value amongst other parameters. The header also defines the functions that make up the interface of the threshold type API. The threshold Type API requires the following interface functions to be implemented.

-
  ```
  static bool threshold_type_is_above_threshold(
        state_t value, threshold_type_pointer_t threshold_type)
  ```
  Determines if the threshold has been reached; if the neuron is to spike, given the value of the state variable, true is returned, otherwise false is returned.

See `my_threshold_type.h` for an example of an implementation of a threshold type.

### Additional inputs

The additional input header file defines the `additional_input_t` data structure, which declares the parameters required for the additional input. The header also defines the functions that make up the interface of the additional input type API. The additional input Type API requires the following interface functions to be implemented:

-
  ```
  static input_t additional_input_get_input_value_as_current(
          additional_input_pointer_t additional_input, state_t membrane_voltage)
  ```
  Gets the value of current provided by the additional input. This may or may not be dependent on the membrane voltage.

-
  ```
  static void additional_input_has_spiked(
          additional_input_pointer_t additional_input)
  ```
  Notifies the additional input type that the neuron has spiked.

See `my_additional_input.h` for an example of an implementation of an additional input type.

## Python Model Builds

Once the C code has been constructed, the PyNN model must be created in Python to translate the PyNN parameters into a form that the C code can understand. In PyNN, populations can be made up of an arbitrary number of neurons, however to maintain real-time operation the number of neurons that are simulated on each core must be limited. The PACMAN module is used by sPyNNaker to partition the populations into subpopulations, based on the specified maximum number of atoms per core of the model, as well as the resources required by the synaptic matrix. The DataSpecification module is then used to write the data for each subpopulation. This is then loaded onto the machine, along with the binary executable, using SpiNNMan.

As with the C code, there are number of components that can be re-used, so that only properties relevant to the new model itself need to be defined. This is done by constructing an individual component for:

1. Neuron model,
2. Input type,
3. Synapse type,
4. Threshold type,
5. Additional input.

These 5 components are then handed over to the main interface object that every neuron model has to extend.

If we look at `my_model_curr_exp.py` in the `python_models8->neuron->builds` directory, we will see the code shown in **Code 4** where the my_model_curr_exp builds its components and hands them over to the main sPyNNaker interface. The breakdown is as follows:

1. On Lines 97 and 98 the neuron model component is created.
2. On Lines 102 and 103 the synapse type component is created.
3. On Line 107 the input type component is created.
4. On Line 111 the threshold type component is created.
5. Line 115 shows that this model does not contain any additional input components.
6. Lines 119 to 135 show the handing over of these separate components to the sPyNNaker main system which will handle all the python support. Note that the binary must match the name of the aplx file generated by the C code.

```
95 .    # TODO: create your neuron model class (change if required)
96.     # create your neuron model class
97.     neuron_model = MyNeuronModel(
98.         n_neurons, i_offset, my_parameter)
```

```

# TODO: create your synapse type model class (change if required)
# create your synapse type model
synapse_type = SynapseTypeExponential(
   n_neurons, tau_syn_E, tau_syn_I, isyn_exc, isyn_inh)

# TODO: create your input type model class (change if required)
# create your input type model
input_type = InputTypeCurrent()

# TODO: create your threshold type model class (change if required)
# create your threshold type model
threshold_type = ThresholdTypeStatic(n_neurons, v_thresh)

# TODO: create your own additional inputs (change if required).
# create your own additional inputs
additional_input = None

# instantiate the sPyNNaker system by initializing
#  the AbstractPopulationVertex
AbstractPopulationVertex.__init__(

    # standard inputs, do not need to change.
    self, n_neurons=n_neurons, label=label,
    spikes_per_second=spikes_per_second,
    ring_buffer_sigma=ring_buffer_sigma,
    incoming_spike_buffer_size=incoming_spike_buffer_size,

    # TODO: Ensure the correct class is used below
    max_atoms_per_core=(
            MyModelCurrExpBase._model_based_max_atoms_per_core),

    # These are the various model types
    neuron_model=neuron_model, input_type=input_type,
    synapse_type=synapse_type, threshold_type=threshold_type,
    additional_input=additional_input,

    # TODO: Give the model a name (shown in reports)
    model_name="MyModelCurrExpBase",

    # TODO: Set this to the matching binary name
    binary="my_model_curr_exp.aplx")
```

**Code 4: Subsection of the my_model_curr_exp.py class**

Take care to note that the same components are used in the Python as are used in the C code's *Makefile*. This means for every new component you add for a neuron build in C which is not originally supported by the sPyNNaker tools, you need to build a corresponding Python component file.

In the new_template folder there are a set of template files within the template directory for each python component. These are located under `python_models8->neuron`. These detail the parts of the class that need to be changed for your model.

## PyNN 0.8 only

If you are using PyNN 0.8, then in addition to the above file (e.g. my_model_curr_exp) in `python_models8->neuron->builds`, you will also need to add a data holder for the corresponding build. For an example, see my_model_curr_exp_data_holder in `python_models8->model_data_holders`.

## Python __init__.py files

Most of the __init__.py files in the template do not contain any code. The one within `python_models8` is the exception; this file adds the `model_binaries` module to the executable paths, allowing sPyNNaker to search this folder for your compiled binary. You can also import your module here to make it easy to use in other scripts.

## Python setup.py file

This file enables you to install the new module. This is set up to install all the modules in the template; if you add any modules, these also need to be added to this file (it is not recursive; each module has to be added separately). To add the module to your python environment in such a way that you can still edit it, you can run:

```
[sudo] python setup.py develop [--user]
```

You need to use `sudo` if you are installing centrally on Linux or Mac OS X; on Windows you need to be in an Administrative console. Add `--user` instead if you want to install only for your username (you shouldn't mix these two options, or you will end up installing it only for the root user).

## Using your module

In order to use the new module, you need to import your module in addition to PyNN e.g. for the template module, you can do the following:

```
import pyNN.spiNNaker as p
from python_models.neuron.builds.my_model_curr_exp import MyModelCurrExp
pop = p.Population(1, MyModelCurrExp, {})
```

A more detailed example is shown in the template in `examples/my_example.py`.

## Task 1: Simple Neuron Model [Easy]

This task will create a simple neural model using the template, and execute it on SpiNNaker.

1. Change the `my_neuron_model_impl.c` and `.h` templates by adding two parameters, one representing a decay and one representing a rest voltage. The parameters should be `REAL` values.

2. Change the model to subtract the difference between the current voltage and the rest voltage multiplied by the decay from the membrane voltage, before adding the total input i.e.

   ```
   v_membrane = v_membrane - ((v_membrane - v_rest) * decay) + input
   ```

3. Recompile the binary.

4. Update the python code model to accept the new decay and rest voltage parameters, ensuring that they match the order of the C code (use `DataType.S1615`). Add getters and setters for the values and update the number of neuron parameters.

5. Update the python code builds to accept the new parameters with default values of 0.1 for decay and -65.0 for the rest voltage.

Run the example script and see what happens.

## Task 2: Conductance-based Model [Moderate]

This task will build a conductance-based model.

1. Make a copy of the C build folder for my_model_curr_exp to my_model_cond_exp.

2. Change the Makefile so that it uses the conductance input type and ensure that the binary name is different from the current based model.

3. Build the binary.

4. Copy the python model `my_model_curr_exp.py` to `my_model_cond_exp.py` and update the code to use the conductance input type, including adding the new required parameters for conductance, and the binary name and model name.

5. Update the example script to use the new model, adjusting the weights to be conductances (usually much smaller values e.g. 0.1 should be enough)

Run the example script and see what happens.

## Task 3: Stochastic Threshold Model [Hard]

This task will create a new threshold model for stochastic thresholds.

1. Update the template threshold type `my_threshold_type.c` and `.h`, removing the parameter my_param, and adding a parameter representing the probability of the neuron firing if it is over the threshold value. This will be a `uint32_t` value in C (see later for details).
2. Add another parameter which is the seed of the random number generator. This is an array of 4 `uint32_t` values for the simplest random number generator in `random.h` (from the spinn_common library - as this should have been installed, you can use `#include <random.h>`).
3. Update the threshold calculation so that when the membrane voltage is over the threshold voltage, the RNG is called with the seed (`mars_kiss64_seed(mars_kiss64_seed_t seed)`).
4. Update the threshold calculation to only result in a spike if the value returned from the RNG is greater than than the probability value.
5. Rebuild the C code.
6. Update the `my_threshold_type.py` python code to include the new parameters, and to generate the random seed. The probability parameter will be between 0 and 1 in Python (default of 0.5), but as the random number generator generates an integer value, this should be converted into a `uint32_t` value between 0 and 0x7FFFFFFF. The seed can be generated using a PyNN RNG, which can be provided to the model as a parameter. Once generated, the seed should be validated using:

   ```
   spynnaker.pyNN.utilities.utility_calls.validate_mars_kiss_64_seed(seed)
   ```

   where `seed` is an array of 4 integer values. Note that `seed` will be updated in place.
7. Update the `my_model_curr_exp_my_threshold_type.py` build to include the new parameters and pass them in to the threshold type. Make rng an optional parameter, which if not set uses a new NumpyRNG.
8. Update the example script to decrease the threshold value to ensure that the model fires.

Run the example script and see how the number of spikes differs for different settings of the spike probability.