

# MIIND : A Model-Agnostic Simulator of Neural Populations

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## 2 ABSTRACT

3 MIIND is a software platform for easily and efficiently simulating the behaviour of interacting  
4 populations of point neurons governed by any 1D or 2D dynamical system. The simulator is  
5 entirely agnostic to the underlying neuron model of each population and provides an intuitive  
6 method for controlling the amount of noise which can significantly affect the overall behaviour. A  
7 network of populations can be set up quickly and easily using MIIND's XML-style simulation file  
8 format describing simulation parameters such as how populations interact, transmission delays,  
9 post-synaptic potentials, and what output to record. During simulation, a visual display of each  
10 population's state is provided for immediate feedback of the behaviour and population activity  
11 can be output to a file or passed to a Python script for further processing. The Python support  
12 also means that MIIND can be integrated into other software such as The Virtual Brain. MIIND's  
13 population density technique is a geometric and visual method for describing the activity of each  
14 neuron population which encourages a deep consideration of the dynamics of the neuron model  
15 and provides insight into how the behaviour of each population is affected by the behaviour of its  
16 neighbours in the network. For 1D neuron models, MIIND performs far better than direct simulation  
17 solutions for large populations. For 2D models, performance comparison is more nuanced but the  
18 population density approach still confers certain advantages over direct simulation. MIIND can be  
19 used to build neural systems that bridge the scales between an individual neuron model and a  
20 population network. This allows researchers to maintain a plausible path back from mesoscopic to  
21 microscopic scales while minimising the complexity of managing large numbers of interconnected  
22 neurons. In this paper, we introduce the MIIND system, its usage, and provide implementation  
23 details where appropriate.

24 **Keywords:** Simulator, Neural Population, Population Density, Software, Python, Dynamical Systems, Network, GPU

## 1 INTRODUCTION

### 25 1.1 Population-Level Modeling

26 Structures in the brain at various scales can be approximated by simple neural population networks  
27 based on commonly observed neural connections. There are a great number of techniques to simulate the  
28 behaviour of neural populations with varying degrees of granularity and computational efficiency. At the  
29 highest detail, individual neurons can be modelled with multiple compartments, transport mechanisms, and  
30 other biophysical attributes. Simulators such as GENESIS (Wilson et al., 1988; Bower and Beeman, 2012)  
31 and NEURON (Hines and Carnevale, 2001) have been used for investigations of the cerebellar microcircuit  
32 (D’Angelo et al., 2016) and a thalamocortical network model (Traub et al., 2005). Techniques which  
33 simulate the individual behaviour of point neurons such as in NEST (Gewaltig and Diesmann, 2007), or  
34 the neuromorphic system SpiNNaker (Furber et al., 2014), allow neurons to be individually parameterised  
35 and connections to be heterogeneous. This is particularly useful for analysing information transfer such as  
36 edge detection in the visual cortex. They can also be used to analyse so called finite-size effects where  
37 population behaviour only occurs as a result of a specific realisation of individual neuron behaviour. There  
38 are, however, performance limitations on very large populations in terms of both computation speed and  
39 memory requirements for storing the spike history of each neuron.

40 At a less granular level, rate-based techniques are a widely used practice of modeling neural activity with  
41 a single variable, whose evolution is often described by first-order ordinary differential equations, which  
42 goes back to Wilson and Cowan (1972). The Virtual Brain (TVB) uses these types of models to represent  
43 activity of large regions (nodes) in whole brain networks to generate efficient simulations (Sanz Leon et al.,  
44 2013; Jirsa et al., 2014). TVB demonstrates the benefits of a rate based approach with the Epileptor neural  
45 population model yielding impressive clinical results (Proix et al., 2017). The Epileptor model is based  
46 on the well known Hindmarsh-Rose neuron model (Hindmarsh and Rose, 1984). However, the behaviour  
47 of this and other rate based models is defined at the population level instead of behaviour emerging from  
48 a definition of the underlying neurons. Therefore, these models have less power to explain simulated  
49 behaviours at the microscopic level.

50 Between these two extremes of granularity is a research area which bridges the scales by deriving  
51 population level behaviour from the behaviour of the underlying neurons. So called population density  
52 techniques (PDTs) have been used for many years (Knight, 1972; Knight et al., 1996; Omurtag et al., 2000)  
53 to describe a population of neurons in terms of a probability density function. The transfer function of a  
54 neuron model or even an experimental neural recording can be used to approximate the response from a  
55 population using this technique (Wilson and Cowan, 1972; El Boustani and Destexhe, 2009; Carlu et al.,  
56 2020). However, analytical solutions are often limited to regular spiking behaviour with constant or slowly  
57 changing input. The software we present here, MIIND, provides a numerical solution for populations of  
58 neurons with potentially complex behaviours (for example bursting) receiving rapidly changing noisy input  
59 with arbitrary jump sizes. The noise is usually assumed to be shot noise, but can be non-Markovian (Lai and  
60 de Kamps, 2017). It contains a number of features that make it particularly suitable for dynamical systems  
61 representing neuronal dynamics, such as an adequate handling of boundary conditions that emerge from the  
62 presence of thresholds and reset mechanisms, but is not restricted to neural systems. The dynamical systems  
63 can be grouped in large networks, which can be seen as the model of a neural circuit at the population level.

64 The key idea behind MIIND is shown in Fig. 1A. Here, a population of neurons is simulated. In this case,  
65 the neurons are defined by a conductance based leaky-integrate-and-fire neuron model with membrane  
66 potential and state of the conductance as the two variables. The neuron’s evolution through state space is  
67 given by a two-dimensional dynamical system. The positions of individual neurons change in state space,

both under the influence of the neuron's endogenous dynamics as determined by the dynamical system and of spike trains arriving from neurons in other populations, which cause rapid transitions in state space that are modeled as instantaneous jumps. For the simulation techniques mentioned earlier involving a large number of individual model neuron instances, a practice that we will refer to as Monte Carlo simulation, the population can be represented as a cloud of points in state space. The approach in MIIND, known as a population density technique (PDT) models the probability density of the cloud, shown in Fig. 1 as a heat map, rather than the behaviour of individual neurons. The threshold and reset values of the underlying neuron model are visible in the hard vertical edges of the density in Fig. 1A. In Fig. 1B, the same simulation approach is used for a population of Fitzhugh-Nagumo neurons (FitzHugh, 1961; Nagumo et al., 1962). The Fitzhugh-Nagumo model has no threshold-reset mechanism and so there are no vertical boundaries to the density. As well as being informative in themselves, common population metrics such as average firing rate and average membrane potential can be quickly calculated from these density functions.

## 1.2 The Case for Population Density Techniques

Why use this technique? Omurtag et al. (2000); Nykamp and Tranchina (2000); Kamps (2003); Iyer et al. (2013) have demonstrated that PDTs are much faster than Monte Carlo simulation for 1D models; De Kamps et al. (2019) have shown that while speed is comparable between 2D models and Monte Carlo, memory usage is orders of magnitude lower because no spikes need to be buffered, which accounts for significant memory use in large-scale simulations. In practice, this may make the difference between running a simulation on an HPC cluster or a single PC equipped with a general purpose graphics processing unit (GPU).

Apart from simulation speed, PDTs have been important in understanding population level behaviour analytically. Important questions, such as 'why are cortical networks stable?' (Amit and Brunel, 1997), 'how can a population be oscillatory when its constituent neurons fire sporadically?' (Brunel and Hakim, 1999), 'how does spike shape influence the transmission spectrum of a population?' (Fourcaud-Trocmé et al., 2003) have been analysed in the context of population density techniques, providing insights that cannot be obtained from merely running simulations. A particularly important question, which has not been answered in full is: 'how do rate-based equations emerge from populations of spiking neurons and when is their use appropriate?'. There are many situations where such rate-based equations are appropriate, but some where they are not and their correspondence to the underlying spiking neural dynamics is not always clear (Montbrió et al., 2015; de Kamps, 2013). There is a body of work suggesting that some rate-based equations can be seen as the lowest order of perturbations of a stationary state, and much of this work is PDT-based (Wilson and Cowan, 1972; Gerstner, 1998; Mattia and Del Giudice, 2002, 2004; Montbrió et al., 2015). MIIND opens the possibility to incorporate these theoretical insights into large-scale network models. For example, we can demonstrate the prediction from Brunel and Hakim (1999) that inhibitory feedback on a population can cause a bifurcation and produce resonance. Finally, for a steady state input, the firing rate prediction of a PDT model converges to a transfer function which can be used in artificial spiking neural networks.

## 1.3 Population-level Modeling

For the population density approach we take with MIIND, the time evolution of the probability density function is described by a partial integro-differential equation. We give it here to highlight some of its features, but for an in depth introduction to the formalism and a derivation of the central equations we refer to Omurtag et al. (2000).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial \vec{v}} \cdot \left( \frac{\vec{F}(\vec{v})\rho(\vec{v}, t)}{\tau} \right) = \int_M d\vec{v}' \left\{ W(\vec{v} \mid \vec{v}')\rho(\vec{v}') - W(\vec{v}' \mid \vec{v})\rho(\vec{v}) \right\}, \quad (1)$$

110      $\rho$  is the probability density function defined over a volume of state space,  $M$ , in terms of time,  $t$ , and  
 111   time-dependent variables,  $\vec{v}$ , under the assumption that the neuronal dynamics of a point model neuron is  
 112   given by:

$$\tau \frac{d\vec{v}}{dt} = \vec{F}(\vec{v}), \quad (2)$$

113   where  $\tau$  is the neuron's membrane time constant. Simple models are one-dimensional (1D). For the  
 114   leaky-integrate-and-fire (LIF) neuron:

$$F(v) = -v, \quad (3)$$

115   For a quadratic-integrate-and-fire (QIF) neuron:

$$F(v) = v^2 + I, \quad (4)$$

116   where  $v$  is the membrane potential, and  $I$  can be interpreted as a bifurcation parameter. More complex  
 117   models require a higher dimensional state space. Since such a space is hard to visualise and understand,  
 118   considerable effort has been invested in the creation of effective models. In particular two-dimensional  
 119   (2D) models are considered to be a compromise that allows considerably more biological realism than LIF  
 120   or QIF neurons, but which remain amenable to visualisation and analysis, and can often be interpreted  
 121   geometrically (Izhikevich, 2007). Examples are the Izhikevich simple neuron (Izhikevich, 2003), the  
 122   Fitzhugh-Nagumo neuron (FitzHugh, 1961; Nagumo et al., 1962), and the adaptive-exponential-integrate-  
 123   and-fire neuron (Brette and Gerstner, 2005), incorporating phenomena such as bursting, bifurcations,  
 124   adaptation, and others that cannot be accounted for in a one dimensional model.

125    $W(v' | v')$  in Eq. 1 represents a transition probability rate function. The right hand side of Eq. 1 makes it  
 126   a Master equation. Any Markovian process can be represented by a suitable choice of  $W$ . For example, for  
 127   shot noise, we have

$$W(v' | v) = \nu(\delta(v' - v - h) - \delta(v - v')), \quad (5)$$

128   where  $\nu$  is the rate of the Poisson process generating spike events. The delta functions reflect that an  
 129   incoming spike causes a rapid change in state space, modeled as an instantaneous jump,  $h$ . It depends on the  
 130   particular neural model in what variable the jumps take place. Often models use a so-called delta synapse,  
 131   such that the jump is in membrane potential. In conductance based models, the incoming spike causes a  
 132   jump in the conductance variable (Fig. 1A), and the influence of the incoming spike on the potential is then  
 133   indirect, given by the dynamical system's response to the sudden change in the conductance state.

134   MIIND produces a numerical solution to Eq. 1 for arbitrary 1D or 2D versions of  $\vec{F}(\vec{v})$  (support for 3D  
 135   versions is in development), under a broad variety of noise processes. Indeed, the right hand side of Eq. 1  
 136   can be generalised to non-Markov processes which cannot simply be formulated in terms of a transition  
 137   probability rate function  $W$ . It is possible to introduce a right hand side that entails an integration over a  
 138   past history of the density using a kernel whose shape is determined by a non-Markov process (Lai and  
 139   de Kamps, 2017).

#### 140   **1.4 Quick Start Guide**

141   Before describing the implementation details of MIIND, this section demonstrates how to quickly  
 142   set up a simulation for a simple E-I network of populations of conductance based neurons using the  
 143   MIIND Python library. A rudimentary level of Python experience is needed to run the simulation. In  
 144   most cases, MIIND can be installed via Python pip. Detailed installation instructions can be found in

145 the *README.md* file of the MIIND repository (De Kamps et al., 2020). For this example, we will use a  
 146 pre-written script, *generateCondFiles.py*, to generate the required simulation files which can be found in  
 147 the *examples/quick\_start* directory of the MIIND repository or can be loaded into a working directory using  
 148 the following python command.

149 \$ python -m miind.loadExamples

150 In the *examples/quick\_start* directory, the *generateCondFiles.py* script generates the simulation files,  
 151 *cond.model* and *cond.tmat*.

152 \$ python generateCondFiles.py

153 The contents of *generateCondFiles.py* is given in Listing 1. The two important parts of the script  
 154 are the neuron model function, in this case named *cond()*, and the call to the MIIND function  
 155 *grid\_generate.generate()* which takes a number of parameters which are discussed in detail later.

### **Listing 1. *generateCondFiles.py***

```
156 import miind.grid_generate as grid_generate
157
158 def cond(y,t):
159     E_r = -65e-3
160     tau_m = 20e-3
161     tau_s = 5e-3
162
163     v = y[0];
164     h = y[1];
165
166     v_prime = ( -(v - E_r) - (h * v) ) / tau_m
167     h_prime = -h / tau_s
168
169     return [v_prime, h_prime]
170
171 grid_generate.generate(
172     func = cond,
173     timestep = 1e-04,
174     timescale = 1,
175     tolerance = 1e-6,
176     basename = 'cond',
177     threshold_v = -55.0e-3,
178     reset_v = -65e-3,
179     reset_shift_h = 0.0,
180     grid_v_min = -72.0e-3,
181     grid_v_max = -54.0e-3,
182     grid_h_min = -1.0,
183     grid_h_max = 2.0,
184     grid_v_res = 200,
185     grid_h_res = 200,
186     efficacy_orientation = 'h')
```

187 The *cond()* function should be familiar to those who have used Python numerical integration frameworks  
 188 such as *scipy.integrate*. It takes the two time dependent variables defined by *y[0]* and *y[1]* and a placeholder  
 189 parameter, *t*, for performing a numerical integration. In the function, the user may define how the derivatives  
 190 of each variable are to be calculated. The *generate()* function requires a suitable time step, values for a

191 threshold and reset if needed, and a description of the extent of the state space to be simulated. With this  
 192 structure, the user may define any two dimensional neuron model. The generated files are then referenced  
 193 in a second file which describes a network of populations to be simulated. Listing 2 shows the contents of  
 194 *cond.xml* describing an E-I network which uses the generated files from *generateCondFiles.py*.

**Listing 2.** *cond.xml*

```

195 <Simulation>
196     <WeightType>CustomConnectionParameters</WeightType>
197     <Algorithms>
198         <Algorithm type="GridAlgorithm" name="COND" modelfile="cond.model" tau_refractive="0.0"
199             ↪ transformfile="cond_0_0_0_0_.tmat" start_v="-0.065" start_w="0.0" >
200             <TimeStep>1e-04</TimeStep>
201         </Algorithm>
202         <Algorithm type="RateFunctor" name="ExcitatoryInput">
203             <expression>800.</expression>
204         </Algorithm>
205     </Algorithms>
206     <Nodes>
207         <Node algorithm="ExcitatoryInput" name="INPUT_E" type="EXCITATORY_DIRECT" />
208         <Node algorithm="ExcitatoryInput" name="INPUT_I" type="EXCITATORY_DIRECT" />
209         <Node algorithm="COND" name="E" type="EXCITATORY_DIRECT" />
210         <Node algorithm="COND" name="I" type="INHIBITORY_DIRECT" />
211     </Nodes>
212     <Connections>
213         <Connection In="INPUT_E" Out="E" num_connections="1" efficacy="0.1" delay="0.0"/>
214         <Connection In="INPUT_I" Out="I" num_connections="1" efficacy="0.1" delay="0.0"/>
215         <Connection In="E" Out="I" num_connections="1" efficacy="0.1" delay="0.001"/>
216         <Connection In="E" Out="E" num_connections="1" efficacy="0.1" delay="0.001"/>
217         <Connection In="I" Out="E" num_connections="1" efficacy="-0.1" delay="0.001"/>
218         <Connection In="I" Out="I" num_connections="1" efficacy="-0.1" delay="0.001"/>
219     </Connections>
220     <Reporting>
221         <Display node="E" />
222         <Display node="I" />
223         <Rate node="E" t_interval="0.001" />
224         <Rate node="I" t_interval="0.001" />
225     </Reporting>
226     <SimulationRunParameter>
227         <SimulationName>EINetwork</SimulationName>
228         <t_end>0.2</t_end>
229         <t_step>1e-04</t_step>
230         <name_log>einetwork.log</name_log>
231     </SimulationRunParameter>
232 </Simulation>
```

233 The full syntax documentation for MIIND XML files is given in section 4. Though more compact or  
 234 flexible formats are available, XML was chosen as a formatting style due to its ubiquity ensuring the  
 235 majority of users will already be familiar with the syntax. The *Algorithms* section is used to declare specific  
 236 simulation methods for one or more populations in the network. In this case, a GridAlgorithm named  
 237 *COND* is set up which references the *cond.model* and *cond.tmat* files. A RateFunctor algorithm produces a  
 238 constant firing rate. In the *Nodes* section, two instances of *COND* are created: one for the excitatory and  
 239 inhibitory populations respectively. Two *ExcitatoryInput* nodes are also defined. The *Connections* section

240 allows us to connect the input nodes to the two conductance populations. The populations are connected to  
 241 each other and to themselves with a 1ms transmission delay. The remaining sections are used to define how  
 242 the output of the simulation is to be recorded, and to provide important simulation parameters such as the  
 243 simulation time. By running the following python command, the simulation can be run.

**Listing 3.** Run the cond.xml simulation.

244 \$ python -m miind.run cond.xml

245 The probability density plots for both populations will be displayed in separate windows as the simulation  
 246 progresses. The firing rate of the excitatory population can be plotted using the following commands. Fig.  
 247 2 shows the probability density plots for both populations and average firing rate of population E.

**Listing 4.** Load the cond.xml simulation and plot the average firing rate of population E.

248 \$ python -m miind.miindio sim cond.xml  
 249 \$ python -m miind.miindio rate E

250 Finally, the density function of each population can be plotted as a heat map for a given time in the  
 251 simulation.

**Listing 5.** Plot the probability density of population I at time 0.12s.

252 \$ python -m miind.miindio plot-density I 0.12

253 Later sections will show how the MIIND simulation can be imported into a user defined Python script  
 254 so that input can be dynamically set during simulation and population activity can be captured for further  
 255 processing.

## 2 THE MIIND GRID ALGORITHM

256 MIIND allows the user to simulate populations of any 1D or 2D neuron model. Although much of MIIND's  
 257 architecture is agnostic to the integration technique used to simulate each population, the system is primarily  
 258 designed to make use of its novel population density techniques, grid algorithm and mesh algorithm. Both  
 259 algorithms use a discretisation of the underlying neuron model's state space such that each discrete "cell",  
 260 which covers a small area of state space, is considered to hold a uniform distribution of probability mass.  
 261 In both algorithms, MIIND performs three important steps for each iteration. First, probability mass is  
 262 transferred from each cell to one or more other cells according to the dynamics of the underlying neuron  
 263 model in the absence of any input. The probability mass is then spread across multiple other cells due to  
 264 incoming random spikes. Finally, if the underlying neuron model has a threshold-reset mechanic, such as  
 265 an integrate and fire model, probability mass which has passed the threshold is transferred to cells along  
 266 the reset potential. As it is the most practically convenient method for the user, we will first introduce the  
 267 grid algorithm. We will discuss its benefits and weaknesses, indicating where it may be appropriate to use  
 268 the mesh algorithm instead.

### 2.1 Generating the Grid and Transition Matrix

270 To discretise the state space in the grid method, the user can specify the size and  $M \times N$  resolution of  
 271 a rectangular grid which results in  $MN$  identical rectangular cells, each of which will hold probability  
 272 mass. In the grid algorithm, a transition matrix lists the proportion of mass which moves from each cell to  
 273 (usually) adjacent cells in one time step due to the deterministic dynamics of the underlying neural model.  
 274 To pre-calculate the transitions for each cell, MIIND first translates the vertices of every cell by integrating  
 275 each point forward by one time step according to the dynamics of the underlying neuron model as shown  
 276 in Fig. 3A. As the time step is small, a single Euler step is usually all that is required to avoid large errors

277 (although other integration schemes can be used if required). Each transformed cell is no longer guaranteed  
 278 to be a rectangle and is compared to the original non-transformed grid to ascertain which cells overlap with  
 279 the newly generated quadrilateral. An overlap indicates that some proportion of neurons in the original  
 280 cell will move to the overlapping cell after one time step. In order to calculate the overlap, the algorithm  
 281 in Listing 6 is employed. This algorithm is also used in the geometric method of generating transition  
 282 matrices for the mesh algorithm shown later.

**Listing 6.** A pseudo-code representation of the algorithm used to calculate the overlapping areas between transformed grid cells and the original grid (or for translated cells of a mesh). The proportion of the area of the original cell gives the proportion of probability mass to be moved in each transition.

```

283 For each transformed cell, A, in the grid:
284   Translate all four vertices according to a single Euler step.
285   Split A into two triangles and add them to a triangle list.
286 For each non-transformed cell, B:
287   Set the overlapping area sum to 0.
288   While the triangle list has changed:
289     For each triangle in the list:
290       If the triangle is entirely outside B: add 0 to the sum.
291       If the triangle is entirely within B: add the triangle's area to the sum.
292       If B is entirely within the triangle: add B's area to the sum.
293     Else: For each edge in B:
294       Calculate any intersection points with the edges of the triangle.
295       Triangulate the polygon produced by the original triangle points plus the new intersection
296       → points.
297       Remove the original triangle from the list.
298       Add the newly generated triangles to the list.
299     Calculate the proportion of A taken by the sum.
300     Add the transition from A to B with the proportion to the transition matrix.

```

301 Though the pseudo-code algorithm is order  $N^2$ , there are many ways that the efficiency of the algorithm  
 302 is improved in the implementation. The number of non-transformed cells checked for overlap can be limited  
 303 to only those which lie underneath each given triangle. Furthermore, the outer loop is parallelisable. Finally,  
 304 as the non-transformed cells are axis-aligned rectangles, the calculation to find edge intersections is trivial.  
 305 Fig. 3A shows a fully translated and triangulated cell at the end of the algorithm. Once the transition matrix  
 306 has been generated, it is stored in a file with the extension *.tmat*. Although the regular grid can be described  
 307 with only four parameters (the width, height, X, and Y resolutions), to more closely match the behaviour of  
 308 mesh algorithm, the vertices of the grid are stored in a *.model* file. To simulate a population using the grid  
 309 algorithm, the *.tmat* and *.model* files must be generated and referenced in the XML simulation file.

310 As demonstrated in the quick start guide (section 1.4), to generate a *.model* and *.tmat* file, the user must  
 311 write a short Python script which defines the underlying neuron model and makes a call to the MIIND API  
 312 to run the algorithm in listing 6. In the *python* directory of the MIIND source repository (see section 1  
 313 in the supplementary material), there are a number of examples of these short scripts. The script used to  
 314 generate a grid for the Izhikevich simple model is listed in the supplementary material section 9.1. The  
 315 required definition of the neuron model function is similar to those used by many numerical integration  
 316 libraries. The function takes a parameter, *y*, which represents a list which holds the two time dependent  
 317 variables and a parameter, *t*, which is a placeholder for use in integration. The function must return the first  
 318 time derivatives of each variable as a list in the same order as in *y*. Once the function has been written, a  
 319 call to *grid\_generate.generate* is made which takes the parameters listed in Table 1.

When the user runs the script, the required *.model* and *.tmat* files will be generated for use in a simulation. In the quick start guide, the conductance based neuron model requires that *efficacy\_orientation* is set to ‘h’ because incoming spikes cause an instantaneous change in the conductance variable instead of the membrane potential. By default, however, this parameter is set to ‘v’. When choosing values for the grid bounds (*grid\_v\_min*, *grid\_v\_max*, *grid\_h\_min*, and *grid\_h\_max*), the aim is to estimate where in state space the population density function might be non-zero during a simulation. In the conductance based neuron model, because of the threshold-reset mechanic, the *grid\_v\_max* parameter need only be slightly above the threshold to ensure that there is at least one column of cells on or above threshold to allow probability mass to be reset. The *grid\_v\_min* value should be below the resting potential and reset potential. However, we must also consider that the neurons could receive inhibitory spikes which would cause the neurons to hyperpolarise. *grid\_v\_min* should therefore be set to a value beyond the lowest membrane potential expected during the simulation. Similarly for the conductance variable, space should be provided for reasonable positive and negative values. If it is known beforehand that no inhibition will occur, however, then the state space bounds can be set tighter in order to improve the accuracy of the simulation using the same grid resolution (*grid\_v\_res* and *grid\_h\_res*). If, during the simulation, probability mass is pushed beyond the lower bounds of the grid, it will be pinned at those lower bounds which will produce incorrect behaviour and results. If the probability mass is pushed beyond the upper bounds, it will be wrapped around to the lower bounds which will also produce incorrect results. The choice of grid resolution is a balance between speed of simulation and accuracy. However, even very coarse grids can produce representative firing rates and behaviours. Typical grid resolutions range between 100x100 and 500x500. It can also be beneficial to experiment with different *M* and *N* values as the accuracy of each dimension can have unbalanced influence over the population level metrics.

342

## 2.2 The Effect of Random Incoming Spikes

The transition matrix in the *.tmat* file describes how probability mass moves to other cells due to the deterministic dynamics of the underlying neuron model. The transition matrix is sparse as probability mass is often only transferred to nearby cells. Solving the deterministic dynamics is therefore very efficient. The mesh algorithm is even faster and, as demonstrated later, is significantly quicker than direct simulation for this part of the algorithm. Another benefit to the modeler is that by rendering the grid with each cell coloured according to its mass, the resultant heat map gives an excellent visualisation of the state of the population as a whole at each time step of the simulation as shown in Fig. 2. This provides particularly useful insight into the sub-threshold behaviour of neurons in the population.

The second step of the grid algorithm, which must be performed every iteration, is to solve the change in the probability density function due to random incoming spikes. It is assumed that a spike causes an instantaneous change in the state of a neuron, usually a step wise jump in membrane potential corresponding to a constant synaptic efficacy. In the conductance based neuron example, this jump is in the conductance. When considering each cell in the grid, a single incoming spike will cause some proportion of the probability mass to shift to at most, two other cells as shown in Fig. 3. Because all cells in the grid are equally distributed and the same size, the relative transition of probability mass caused by a single spike is the same for them all. A sparse transition matrix, *M*, can be generated from this single transition so that applying *M* to the probability density grid applies the transition to all cells. MIIND calculates a different *M* for each incoming connection to the population based on the user defined instantaneous jump, which we refer to as the efficacy. In the mesh algorithm, the relative transitions are different for each cell and so a transition matrix (similar to that of the *.tmat* file) is required to describe the effect of a single spike. As with many other population density techniques, MIIND assumes that incoming spikes are Poisson distributed,

365 although it is possible to approximate other distributions. MIIND uses  $M$  to calculate the change to the  
 366 probability density function,  $\rho$ , due solely to the non-deterministic dynamics as described by equation 6.

$$d\rho/dt = \lambda M \rho \quad (6)$$

367  $\lambda$  is the incoming Poisson firing rate. The boost numeric library is used to integrate  $d\rho/dt$ . The solution  
 368 to this equation describes the spread of the probability density due to Poisson spikes. This ‘master process’  
 369 step amounts to multiple applications of the transition matrix  $M$  and is where the majority of time is taken  
 370 computationally. However, OpenMP is available in MIIND to parallelise the matrix multiplication. If  
 371 multiple cores are available, the OpenMP implementation significantly improves performance of the master  
 372 process step. More information covering this technique can be found in De Kamps et al. (2019); de Kamps  
 373 (2013).

### 374 2.3 Threshold-Reset Dynamics

376 Many neuron models include a “threshold-reset” process such that neurons which pass a certain mem-  
 377 brane potential value are shifted back to a defined reset potential to approximate repolarisation during an  
 378 action potential. To facilitate this in MIIND, after each iteration, probability mass in cells which lie across  
 379 the threshold potential is relocated to cells which lie across the reset potential according to a pre-calculated  
 380 mapping. Often, a refractory period is used to hold neurons at the reset potential before allowing them to  
 381 again receive incoming spikes. In MIIND this is implemented using a queue for each threshold cell as  
 382 shown in Fig. 4. The queues are set to the length of the refractory period divided by the time step, rounded  
 383 up to the nearest integer value. During each iteration, probability mass is shifted one position along the  
 384 queue. A linear interpolation of the final two places in the queue is made and this value is passed to the  
 385 mapped reset cell. The interpolation is required in case the refractory period is not an integer multiple of  
 386 the time step. The total probability mass in the threshold cells each iteration is used to calculate the average  
 387 population firing rate. For models which do not require threshold-reset dynamics, setting the threshold  
 388 value to the maximal membrane potential of the grid, and the reset to the minimal membrane potential  
 389 ensures that no resetting of probability mass will occur.

### 390 2.4 How MIIND Facilitates Interacting Populations

392 The grid algorithm describes how the behaviour of a single population is simulated. The MIIND software  
 393 platform as a whole provides a way for many populations with possibly many different integration  
 394 algorithms to interact in a network. The basic process of simulating a network is as follows. The user must  
 395 write an XML file which describes the whole simulation. This includes defining the population nodes of  
 396 the network and how they are connected; which integration technique each population uses (grid algorithm,  
 397 mesh algorithm etc.); external inputs to the network; how the activity of each population will be recorded  
 398 and displayed; the length and time step of the simulation. As shown in the quick start guide, the XML file  
 399 can be passed as a parameter to the *miind.run* module in Python. When the simulation is run, a population  
 400 network is instantiated and the simulation loop is started. For each iteration, the output activity of each  
 401 population node is recorded. By default, the activity is assumed to be an average firing rate but other options  
 402 are available such as average membrane potential. The outputs are passed as inputs to each population node  
 403 according to the connectivity defined in the XML file. Each population is evolved forward by one time  
 404 step and the simulation loop repeats until the simulation time is up. The Python front end, *miind.miindio*,

405 provides the user with tools to analyse the output from the simulation. A custom *run* script can also be  
406 written by the user to perform further analysis and processing.

407 The simplicity of the XML file means that a user can set up a large network of populations with very  
408 little effort. The model archive in the code repository holds a set of example simulations demonstrating the  
409 range of MIIND’s functionality and includes an example which simulates the Potjans-Diesmann model  
410 of a cortical microcircuit (Potjans and Diesmann, 2014), which is made up of eight populations of leaky  
411 integrate and fire neurons. Fig. 5 shows a representation of the model with embedded density plots for each  
412 population.

## 413 2.5 Running MIIND Simulations

415 The quick start guide demonstrated the simplest way to run a simulation given that the required *.model*,  
416 *.tmat*, and *.XML* files have been generated. The *miind.run* script imports the *miind.miindsim* Python  
417 extension module which can also be imported into any user written Python script. Section 6 details the  
418 functions which are exposed by *miind.miindsim* for use in a python script. The benefit of this method is  
419 that the outputs from populations can be recorded after each iteration and inputs can be dynamic allowing  
420 the python script to perform its own logic on the simulation based on the current state.

421 There is also a command line interface (CLI) program provided by the Python module, *miind.miindio*.  
422 The CLI can be used for many simple work flow tasks such as generating models and displaying results.  
423 Each command which is available in the CLI, can also be called from the MIIND Python API, upon which  
424 the CLI is built. A full list of the available commands in the CLI is given in section 9.3 of the supplementary  
425 material and a worked example using common CLI commands is provided in section 7.

## 426 2.6 When not to use the Grid Algorithm

428 For many underlying neuron models, the grid algorithm will produce results showing good agreement  
429 with direct simulation to a greater or lesser extent depending on the resolution of the grid (see Fig. 6).  
430 However, for models such as exponential integrate and fire, a significantly higher grid resolution is required  
431 than might be expected because of the speed of the dynamics across the threshold (beyond which, neurons  
432 perform the action potential). When the input rate is high enough to generate tonic spiking in an exponential  
433 integrate and fire model, the rate of depolarisation of each neuron reduces as it approaches the threshold  
434 potential then once it is beyond the threshold, quickly increases producing a spike. Because the grid  
435 discretises the state space into regular cells, if cells are large due to a low resolution, only a small number  
436 of cells will span the threshold, as shown in Fig. 7A. When the transition matrix is applied each time  
437 step, probability mass is distributed uniformly across each cell. Probability mass can therefore artificially  
438 cross the threshold much faster than it should leading to a higher than expected average firing rate for the  
439 population. Using the grid algorithm for such models where the firing rate itself is dependent on sharp  
440 changes in the speed of the dynamics should be avoided if high accuracy is required. Other neuron models,  
441 like the bursting Izhikevich simple model, also have sharp changes in speed when neurons transition from  
442 bursting to quiescent periods. However, the bursting firing rate is unaffected by these dynamics and the  
443 oscillation frequency is affected only negligibly due to the difference in timescales. The grid algorithm  
444 is therefore still appropriate in cases such as this. For exponential integrate and fire models, however,  
445 MIIND provides a second algorithm which can more accurately capture the deterministic dynamics: mesh  
446 algorithm.

### 3 THE MIIND MESH ALGORITHM

447 Instead of a regular grid to discretise the state space of the underlying neuron model, the mesh algorithm  
448 requires a two dimensional mesh which describes the dynamics of the neuron model itself in the absence  
449 of incoming spikes. A mesh is constructed from strips which follow the trajectories of neurons in state  
450 space (Fig. 8). The trajectories form so-called characteristic curves of the neuron model from which this  
451 method is inspired (De Kamps et al., 2019; de Kamps, 2013).

452 These trajectories are computed as part of a one-time preprocessing step using an appropriate integration  
453 technique and time step. Strips will often approach or recede from nullclines and stationary points and  
454 their width may shrink or expand according to their proximity to such elements. Each strip is split into  
455 cells. Each cell represents how far along the strip neurons will move in a single time step. As with the  
456 width of the strips, cells will become more dense or more sparse as the dynamics slow down and speed up  
457 respectively. The result of covering the state space with strips is a precomputed description of the model  
458 dynamics such that the state of a neuron in one cell of the mesh is guaranteed to be in the next cell along  
459 the strip after a single time step. Depending on the underlying neuron model, it can be difficult to get full  
460 coverage without cells becoming too small or shear. However, once built, the deterministic dynamics have  
461 effectively been “pre-solved” and baked into the mesh.

462 As with the grid algorithm, when the simulation is running, each cell is associated with a probability  
463 mass value which represents the probability of finding a neuron from the population with a state in that  
464 cell. When a probability density function (PDF) is defined across the mesh, computing the change to the  
465 PDF due to the deterministic dynamics of the neurons is simply a matter of shifting each cell’s probability  
466 mass value along its strip. In the C++ implementation, this requires no more than a pointer update and is  
467 therefore quicker than the grid algorithm for solving the deterministic dynamics as no transition matrix is  
468 applied to the cells.

469 Mesh algorithm does, however, still require a transition matrix to implement the effect of incoming spikes  
470 on the PDF. This transition matrix describes how the state of neurons in each cell are translated in the event  
471 of a single incoming spike. Unlike the grid algorithm, cells are unevenly distributed across the mesh and  
472 are different sizes and shapes. What proportion of probability mass is transferred to which cells with a  
473 single incoming spike is, therefore, different for all cells. During simulation, the total change in the PDF is  
474 calculated by shifting probability mass one cell down each strip and using the transition matrix to solve the  
475 master equation every time step. The combined effect can be seen in Fig. 9. The method of solving the  
476 master equation is explained in detail in de Kamps (2013).

#### 3.1 When not to use the Mesh Algorithm

478 Just as with the grid algorithm, certain neuron models are better suited to an alternative algorithm. In  
479 the mesh algorithm, very little error is introduced for the deterministic dynamics. Probability mass flows  
480 down each strip as it would without the discretisation and error is limited only to the size of the cells.  
481 When the master equation is solved, however, probability mass can spread to parts of state space which  
482 would see less or no mass. Fig. 7B demonstrates how in the mesh algorithm, as probability mass is pushed  
483 horizontally, very shear cells can allow mass to be incorrectly transferred vertically as well. In the the  
484 grid algorithm, error is introduced in the opposite way. Solving the master equation pushes probability  
485 mass along horizontal rows of the grid and error is limited to the width of the row. The grid algorithm is  
486 preferable over the mesh algorithm for populations of neurons with one fast variable and one slow variable  
487 which can produce very shear cells in a mesh, e.g. in the Fitzhugh-Nagumo model (De Kamps et al., 2019).  
488 In both algorithms, the error can be reduced by increasing the density of cells (by increasing the resolution

489 of the grid, or by reducing the timestep and strip width of the mesh). However, better efficiency is achieved  
490 by using the appropriate algorithm.

### 491 3.2 Building a Mesh for the Mesh Algorithm

492 Before a simulation can be run for a population which uses the mesh algorithm, the pre-calculation steps  
493 of generating a mesh and transition matrices must be performed. Fig. 10 shows the full pre-processing  
494 pipeline for mesh algorithm. The mesh is a collection of strips made up of quadrilateral cells. As mentioned  
495 earlier, probability mass moves along a strip from one cell to the next each time step which describes  
496 the deterministic dynamics of the model. Defining the cells and strips of a 2D mesh is not generally a  
497 fully automated process and the points of each quadrilateral must be defined by the mesh developer and  
498 stored in a *.mesh* file. When creating the mesh, the aim is to cover as much of the state space as possible  
499 without allowing cells to get too small or misshapen. An example of a full mesh generation script for  
500 the Izhikevich simple neuron model (Izhikevich, 2003) is available in section 9.1 of the supplementary  
501 material. MIIND provides *miind.miind.api.LifMeshGenerator*, *miind.miind.api.QifMeshGenerator*, and  
502 *miind.miind.api.EifMeshGenerator* scripts to automatically build the 1D leaky integrate and fire, quadratic  
503 integrate and fire, and exponential integrate and fire neuron meshes respectively. They can be called from  
504 the CLI. The scripts generate the three output files which any mesh generator script must produce: a *.mesh*  
505 file, a *.stat* file which defines extra cells in the mesh to hold probability mass that has settled at a stationary  
506 point, and a *.rev* file which defines a “reversal mapping” indicating how probability mass is transferred  
507 from strips in the mesh to the stationary cells. More information on *.mesh*, *.stat*, and *.rev* files is provided  
508 in the supplementary material section 6.

509 Once the *.mesh*, *.stat*, and *.rev* files have been generated by the user or by one of the automated 1D  
510 scripts, the Python command line interface, *miind.miindio*, provides commands to convert the three files  
511 into a single *.model* file and generate transition matrices stored in *.mat* files. The model file is what will be  
512 referenced and read by MIIND to load a mesh for a simulation. To generate this file, use the CLI command,  
513 **generate-model**. The command parameters are shown in Table 2. All input files must have the same base  
514 name, for example: *lif.mesh*, *lif.stat*, and *lif.rev*. If the command runs successfully, a new file will be created:  
515 *basename.model*. A number of pre-generated models are available in the *examples* directory of the MIIND  
516 repository to be used “out of the box” including the adaptive exponential integrate and fire and conductance  
517 based neuron models.

#### 518 Listing 7. Generate a Model in the CLI

```
> generate-model lif -60.0 -30.0
```

519 The generated *.model* file contains the mesh vertices, some summary information such as the time step  
520 used to generate the mesh and the threshold and reset values, and a mapping of threshold cells to reset cells.

521 In the the mesh algorithm, transition matrices are used to solve the Poisson master equation which  
522 describes the movement of probability mass due to incoming random spikes. In the mesh algorithm, one  
523 transition matrix is required for each post synaptic efficacy that will be needed in the simulation. So if a  
524 population is going to receive spikes which cause jumps of 0.1mV and 0.5mV, two transition matrices are  
525 required. It is demonstrated later how the efficacy can be made dependent on the membrane potential or  
526 other variables. Each transition matrix is stored in a *.mat* file and contains a list of source cells, target cells,  
527 and proportions of probability mass to be transferred to each. For a given cell in the mesh, neurons with a  
528 state inside that cell which receive a single external spike will shift their location in state space by the value  
529 of the efficacy. Neurons from the same cell could therefore end up in many other different cells, though  
530 often ones which are nearby. It is assumed that neurons are distributed uniformly across the source cell.

531 Therefore, the proportion of neurons which end up in each of the other cells can be calculated. MIIND  
 532 performs this calculation in two ways, the choice for which is given to the user.

533 The first method is to use a Monte Carlo approach such that a number of points are randomly placed in  
 534 the source cell then translated according to the efficacy. A search takes place to find which cells the points  
 535 were translated to and the proportions are calculated from the number of points in each. For many meshes,  
 536 a surprisingly small number of points, around 10, is required in each cell to get a good approximation  
 537 for the transition matrix and the process is therefore quite efficient. As shown in Fig. 10, an additional  
 538 process is required when generating transition matrices using Monte Carlo which includes two further  
 539 intermediate files, *.fid* and *.lost*. All points must be accounted for when performing the search and in cases  
 540 where points are translated outside of the mesh, an exhaustive search must be made to find the closest cell.  
 541 The **lost** command allows the user to speed up this process which is covered in detail in section 6.1 of the  
 542 supplementary material.

543 The second method translates the actual vertices of each cell according to the efficacy and calculates the  
 544 exact overlapping area with other cells. The method by which this is achieved is the same as that used to  
 545 generate the transition matrix of the grid algorithm, described in section 2.1. This method provides much  
 546 higher accuracy than Monte Carlo but is one order of magnitude slower (it takes a similar amount of time  
 547 to perform Monte Carlo with 100 points per cell). For some meshes, it is crucial to include very small  
 548 transitions between cells to properly capture the dynamics which justifies the need for the slower method.  
 549 It also benefits from requiring no additional user input in contrast to the Monte Carlo method.

550 In *miind.miindio*, the command **generate-matrix** can be used to automatically generate each *.mat*  
 551 file. In order to work, there must be a *basename.model* file in the working directory. The **generate-**  
 552 **matrix** command takes six parameters which are described in Table 3. Listing 8 shows an example of the  
 553 **generate-matrix** command. If successful, two files are generated: *basename.mat* and *basename.lost*.

**Listing 8.** The *miind.miindio* command to generate a matrix using the *adex.model* file with an efficacy of  
 0.1 in *v* and a jump of 5.0 in *w* when a neuron spikes. The Monte Carlo method has been chosen with 10  
 points per cell.

554 > generate-matrix adex 0.1 10 0.0 5.0 false

555 Once **generate-matrix** has completed, a *.mat* file will have been generated and the *.model* file will have  
 556 been amended to include a *<Reset Mapping>* section. Similar to the reversal mapping in the *.rev* file,  
 557 the reset mapping describes movement of probability mass from the cells which lie across the threshold  
 558 potential to cells which lie across the reset potential. If the threshold or reset values are changed but no  
 559 other change is made to the mesh, it can be helpful to re-run the mapping calculation without having  
 560 to completely re-calculate the transition matrix. *miind.miindio* provides the command **regenerate-reset**  
 561 which takes the base name and any new reset shift value (0 if not required) as parameters. This will quickly  
 562 replace the reset mapping in the *.model* file.

**Listing 9.** The user may change the *<Threshold>* and *<Reset>* values in the *.model* file (or re-call  
**generate-model** with different threshold and reset values) then update the existing Reset Mapping. In this  
 case, the *adex.model* was updated with a reset *w* shift value of 7.0.

563 > regenerate-reset adex 7.0

564 With all required files generated, a simulation using the mesh algorithm can now be run in MIIND.

565 **3.3 Jump Files**

566 In some models, it is helpful to be able to set the efficacy as a function of the state. For example,  
 567 to approximate adaptive behaviour where the post synaptic efficacy lowers as the membrane potential  
 568 increases. Jump files have been used in MIIND to simulate the Tsodyks-Markram (Tsodyks and Markram,  
 569 1997) synapse model as described in De Kamps et al. (2019). In the model, one variable/dimension is  
 570 required to represent the membrane potential,  $V$ , of the post-synaptic neuron and the second to represent  
 571 the synaptic contribution,  $G$ .  $G$  and  $V$  are then used to derive the post-synaptic potential caused by an  
 572 incoming spike. Before generating the transition matrix, each cell can be assigned its own efficacy for  
 573 which the transitions will be calculated. During generation, Monte Carlo points will be translated according  
 574 to that value instead of a constant across the entire mesh. When calling the **generate-matrix** command, a  
 575 separate set of three parameters is required to use this feature. The base name of the model file, the number  
 576 of Monte Carlo points per cell, and a reference to a *jump* file which stores the efficacy values for each cell  
 577 in the mesh.

**Listing 10.** Generate a transition matrix with a jump file in the CLI

578 > generate-matrix adex 10 adex.jump

579 As with the files required to build the mesh, the jump file must be user generated as the efficacy values may  
 580 be non-linear and involve one or both of the dimensions of the model. The format of a jump file is shown  
 581 in listing 11. The *<Efficacy>* element of the XML file gives an efficacy value for both dimensions of the  
 582 model and is how the resulting transition matrix will be referenced in the simulation. The *<Translations>*  
 583 element lists the efficacy in both dimensions for each cell in the mesh.

**Listing 11.** The format of the jump file. Each line in the *<Translations>* block gives the strip,cell  
 coordinates of the cell followed by the  $h$  efficacy then the  $v$  efficacy. The *<Efficacy>* element gives a  
 reference efficacy which will be used to reference the transition matrix built with this jump file. It must  
 therefore be unique among jump files used for the same model.

584 <Jump>  
 585 <Efficacy>0.0 0.1</Efficacy>  
 586 <Translations>  
 587 0,0 0.0 0.1  
 588 1,0 0.0 0.1  
 589 1,1 0.0 0.10012  
 590 1,2 0.0 0.10045  
 591 ...  
 592 </Translations>  
 593 </Jump>

594 After calling **generate-matrix**, as before, the *.mat* file will be created with the quoted values in the  
 595 *<Efficacy>* element of the jump file. As with the vanilla Monte Carlo generation, the additional process of  
 596 tracking lost points must be performed.

## 4 WRITING THE XML FILE

597 MIIND provides an intuitive XML style language to describe a simulation and its parameters. This  
 598 includes descriptions of populations, neuron models, integration techniques, and connectivity as well  
 599 as general parameters such as time step and duration. The XML file is split into sections which are sub  
 600 elements of the XML root node, *<Simulation>*. They are Algorithms, Nodes, Connections, Reporting, and  
 601 SimulationRunParameter. These elements make up the major components of a MIIND simulation.

---

## 602 4.1 Algorithms

603 An *<Algorithm>* in the XML code describes the simulation method for a population in the network. The  
 604 nodes of the network represent separate instances of these algorithm elements. Therefore, many nodes can  
 605 use the same algorithm. Each algorithm has different parameters or supporting files but as a minimum, all  
 606 algorithms must declare a type and a name. Each algorithm is also implicitly associated with a “weight  
 607 type”. All algorithms used in a single simulation must be compatible with the weight type as it describes the  
 608 way that populations interact. The *<WeightType>* element of the XML file can take the values, “double”,  
 609 “DelayedConnection”, or “CustomConnectionParameters”. Which value the weight type element takes  
 610 influences which algorithms are available in the simulation and how the connections between populations  
 611 will be defined. The following sections cover all Algorithm types currently supported in MIIND. Table 4  
 612 lists these algorithms and their compatible weight types.

### 613 4.1.1 RateAlgorithm

614 RateAlgorithm is used to supply a Poisson distributed input (with a given average firing rate) to other  
 615 nodes in the simulation. It is typically used for simulating external input. The *<rate>* sub-element is used  
 616 to define the activity value which is usually a firing rate.

#### Listing 12. A RateAlgorithm definition with a constant rate of 100Hz.

```
617 <Algorithm name="Cortical Background Algorithm" type="RateAlgorithm">
618   <rate>100.0</rate>
619 </Algorithm>
```

## 620 4.1.2 MeshAlgorithm and MeshAlgorithmCustom

621 In section 3.2, we saw how to generate *.model* and *.mat* files. These are required to simulate a population  
 622 using the mesh algorithm. Algorithm type=MeshAlgorithm tells MIIND to use this technique. The model  
 623 file is referenced as an attribute to the Algorithm definition. The *TimeStep* child element must match that  
 624 which was used to generate the mesh. This value is quoted in the model file. As many *MatrixFile* elements  
 625 can be declared as are required for the simulation, each with an associated *.mat* file reference.

#### Listing 13. A MeshAlgorithm definition with two matrix files.

```
626 <Algorithm type="MeshAlgorithm" name="ALG_ADEX" modelfile="adex.model" >
627   <TimeStep>0.001</TimeStep>
628   <MatrixFile>adex_0.05_0_0_.mat</MatrixFile>
629   <MatrixFile>adex_-0.05_0_0_.mat</MatrixFile>
630 </Algorithm>
```

631 MeshAlgorithm provides two further optional attributes in addition to *modelfile*. The first is *tau\_refractive*  
 632 which enables a refractory period and the second is *ratemethod* which takes the value “AvgV” if the activity  
 633 of the population is to be represented by the average membrane potential. Any other value for *ratemethod*  
 634 will set the activity to the default average firing rate. The activity value is what will be passed to other  
 635 populations in the network as well as what will be recorded as the activity for any populations using this  
 636 algorithm.

637 When the weight type is set to CustomConnectionParameters, the type of this algorithm definition should  
 638 be changed to MeshAlgorithmCustom. No other changes to the definition are required.

### 639 4.1.3 GridAlgorithm and GridJumpAlgorithm

640 For populations which use the grid algorithm, the following listing is required. Similar to the MeshAl-  
 641 gorithm, the model file is referenced as an attribute. However, there are no matrix files required as the  
 642 transition matrix for solving the Poisson master equation is calculated at run time. The transition matrix

643 for the deterministic dynamics, stored in the *.tmat* file, is referenced as an attribute as well. Attributes for  
 644 *tau\_refractive* and *ratemethod* are also available with the same effects as for MeshAlgorithm.

**Listing 14.** A GridAlgorithm definition using the AvgV (membrane potential) rate method.

```
645 <Algorithm type="GridAlgorithm" name="GRIDALG_FN" modelfile="fn.model" tau_refractive="0.0"
646   ↪ transformfile="fn_0_0_0_0_.tmat" start_v="-1.0" start_w="-0.3" ratemethod="AvgV">
647 <TimeStep>0.00001</TimeStep>
648 </Algorithm>
```

649 GridAlgorithm also provides additional attributes *start\_v* and *start\_w* which allows the user to set the  
 650 starting state of all neurons in the population which creates an initial probability mass of 1.0 in the  
 651 corresponding grid cell at the start of the simulation.

652 GridJumpAlgorithm provides a similar functionality as MeshAlgorithm when the transition matrix is  
 653 generated using a jump file. That is, the efficacy applied to each cell when calculating transitions differs  
 654 from cell to cell. In GridJumpAlgorithm, the efficacy at each cell is multiplied by the distance between  
 655 the central *v* value of the cell and a user defined “stationary” value. The initial efficacy and the stationary  
 656 values are defined by the user in the XML *<Connection>* elements. GridJumpAlgorithm is useful for  
 657 approximating populations of neurons with a voltage dependent synapse.

**Listing 15.** A GridJumpAlgorithm definition and corresponding Connection with a “stationary” attribute.  
 The efficacy at each grid cell will equal the original efficacy value (-0.05) multiplied by the difference  
 between each cell’s central *v* value and the given stationary value (-65)

```
658 <Algorithm type="GridJumpAlgorithm" name="ALG_ADEX" modelfile="adex.model" tau_refractive="0.0"
659   ↪ transformfile="adex_0_0_0_0_.tmat" start_v="-65.0" start_w="0.0">
660 <TimeStep>0.0001</TimeStep>
661 </Algorithm>
662 ...
663 <Connection In="BG_NOISE" Out="ADEX_NODE" num_connections="1" efficacy="-0.05" delay="0.0" stationary="
664   ↪ -65.0"/>
```

#### 665 4.1.4 Additional Algorithms

666 MIIND also provides OUAlgorithm and WilsonCowanAlgorithm. The OUAlgorithm generates an  
 667 Ornstein–Uhlenbeck process (Uhlenbeck and Ornstein, 1930) for simulating a population of LIF neurons.  
 668 The WilsonCowanAlgorithm implements the Wilson–Cowan model for simulating population activity  
 669 (Wilson and Cowan, 1972). Examples of these algorithms are provided in the examples directory of the  
 670 MIIND repository (*examples/twopop* and *examples/model\_archive/WilsonCowan*).

671 One final algorithm, RateFunctor, behaves similarly to RateAlgorithm. However, instead of a rate  
 672 value, the child value defines the activity using a C++ expression in terms of variable, *t*, representing the  
 673 simulation time.

**Listing 16.** A RateFunctor algorithm definition in which the firing rate linearly increases to 100Hz over  
 0.1 seconds and remains at 100Hz thereafter.

```
674 <Algorithm type="RateFunctor" name="ExternalInput">
675   <expression><! [CDATA[ t < 0.1 ? (t/0.1)*100 : 100 ]]></expression>
676 </Algorithm>
```

677 A CDATA expression is not permitted when using MIIND in Python or when calling *miind.run*. However,  
 678 RateFunctor can still be used with a constant expression (although this has no benefit beyond what

679 RateAlgorithm already provides). CDATA should only be used when MIIND is built from source (not  
 680 installed using pip) and the MIIND API is used to generate C++ code from an XML file.

## 681 4.2 Nodes

682 The `<Node>` block lists instances of the Algorithms defined above. Each node represents a single  
 683 population in the network. To create a node, the user must provide the name of one of the algorithms  
 684 defined in the algorithm block which will be instantiated. A name must also be given to uniquely identify  
 685 this node. The type describes the population as wholey inhibitory, excitatory, or neutral. The type dictates  
 686 the sign of the post synaptic efficacy caused by spikes from this population. Setting the type to neutral  
 687 allows the population to produce both excitatory and inhibitory (positive and negative) synaptic efficacies.  
 688 For most algorithms, the valid types for a node are *EXCITATORY*, *INHIBITORY*, and *NEUTRAL*. *EXCITA-*  
*TORY\_DIRECT* and *INHIBITORY\_DIRECT* are also available but mean the same as *EXCITATORY* and  
 690 *INHIBITORY* respectively.

**Listing 17.** Three nodes defined in the Nodes section using the types *NEUTRAL*, *INHIBITORY*, and  
*EXCITATORY* respectively.

```
691 <Nodes>
692 ...
693 <Node algorithm="GRIDALG_FN" name="POP_1" type="NEUTRAL" />
694 <Node algorithm="ALG_ADEX" name="ADEX_NODE" type="INHIBITORY" />
695 <Node algorithm="RATEFUNC_BACKGROUND" name="BG_NOISE" type="EXCITATORY" />
696 ...
697 </Nodes>
```

698 Many nodes can reference the same algorithm to use the same population model but they will behave  
 699 independently based on their individual inputs.

## 700 4.3 Connections

701 The connections between the nodes are defined in the `<Connections>` sub-element. Each connection  
 702 can be thought of as a conduit which passes the output activity from the “In” population node to the “Out”  
 703 population node. The format used to define the connections is dependent on the choice of *WeightType*.  
 704 When the type is *double*, connections require a single value which represents the connection weight. This  
 705 will be multiplied by the output activity of the In population and passed to the Out population. The sign of  
 706 the weight must match the In node’s type definition (*EXCITATORY*, *INHIBITORY*, *NEUTRAL*).

**Listing 18.** A simple double WeightType Connection with a single rate multiplier.

```
707 <WeightType>double</WeightType>
708 <Connections>
709 ...
710 <Connection In="RATEFUNC_BACKGROUND" Out="WC_POP">0.1</Connection>
711 ...
712 </Connections>
```

713 Many algorithms use the *DelayedConnection* weight type which requires three values to define each  
 714 connection. The first is the number of incoming connections each neuron in the Out population receives  
 715 from the In population. This number is effectively a weight and is multiplied by the output activity of the In  
 716 population. For example, if the output firing rate of an In population is 10Hz and the number of incoming  
 717 connections is set to 10, the effective average incoming spike rate to each neuron in the Out population  
 718 will be 100 Hz. The second value is the post synaptic efficacy whose sign must match the type of the In  
 719 population. If the Out population is an instance of MeshAlgorithm, the efficacy must also match one of the

720 provided .mat files. The third value is the connection delay in seconds. The delay is implemented in the  
 721 same way as the refractory period in the mesh and grid algorithms. The output activity of the In population  
 722 is placed at the beginning of the queue and shifted towards the end of the queue over subsequent iterations.  
 723 The input to the Out population is taken as the linear interpolation between the final two values in the  
 724 queue.

**Listing 19.** A DelayedConnection with number of connections = 10, efficacy = 0.1, and delay of 1ms.

```
725 <WeightType>DelayedConnection</WeightType>
726 <Connections>
727 ...
728 <Connection In="RATEFUNC_BACKGROUND" Out="BURSTER">10 0.1 0.001</Connection>
729 ...
730 </Connections>
```

731 With the addition of GridAlgorithm, there was a need for a more flexible connection type which would  
 732 allow custom parameters to be applied to each connection. When using the *CustomConnectionParameters*  
 733 weight type, the key-value attributes of the connections are passed as strings to the C++ implementation.  
 734 By default, custom connections require the same three values as *DelayedConnection*: *num\_connections*,  
 735 *efficacy*, and *delay*. *CustomConnectionParameters* can therefore be used with mesh algorithm nodes as  
 736 well as grid algorithm nodes although MeshAlgorithm definitions must have the type attribute set to  
 737 MeshAlgorithmCustom instead.

**Listing 20.** A MeshAlgorithmCustom definition for use with WeightType=CustomConnectionParameters  
 and a Connection using the num\_connections, efficacy, and delay attributes.

```
738 <WeightType>CustomConnectionParameters</WeightType>
739
740 <Algorithms>
741 ...
742 <Algorithm type="MeshAlgorithmCustom" name="ALG_ADEX" modelfile="adex.model" >
743   <TimeStep>0.001</TimeStep>
744   <MatrixFile>adex_0.05_0_0_0_.mat</MatrixFile>
745   <MatrixFile>adex_-0.05_0_0_0_.mat</MatrixFile>
746 </Algorithm>
747 ...
748 </Algorithms>
749
750
751 <Connections>
752 ...
753 <Connection In="ALG_ADEX" Out="RG_E" num_connections="1" efficacy="0.05" delay="0.0"/>
754 ...
755 </Connections>
```

756 Other combinations of attributes for connections using CustomConnectionParameters are available for  
 757 use with specific specialisations of the grid algorithm which are discussed in section 4 of the supplementary  
 758 material. Any number of attributes are permitted but they will only be used if there is an algorithm  
 759 specialisation implemented in the MIIND code base.

#### 760 4.4 SimulationRunParameter

761 The *<SimulationRunParameter>* block contains parameter settings for the simulation as a whole. The  
 762 sub-elements listed in Table 5 are required for a full definition. Although most of the sub-elements are

763 self explanatory, *t\_step* has the limitation that it must match or be an integer multiple of all time steps  
 764 defined by any MeshAlgorithm and GridAlgorithm instances. *master\_steps* is used only for the GPGPU  
 765 implementation of MIIND (section 5). It allows the user to set the number of Euler iterations per time  
 766 step to solve the master equation. By default, the value is 10. However, to improve accuracy or to avoid  
 767 blow-up in the case where the time step is too large or the local dynamics are unstable, *master\_steps* should  
 768 be increased.  
 769

#### 4.5 Reporting

770 The *<Reporting>* block is used to describe how output is displayed and recorded from the simulation.  
 771 There are three ways to record output from the simulation: Density, Rate, and Display. The *<Rate>*  
 772 element takes the node *name* and *t\_interval* as attributes and creates a single file in the output directory.  
 773 *t\_interval* must be greater than or equal to the simulation time step. At each *t\_interval* of the simulation, the  
 774 output activity of the population is recorded on a new line of the generated file. Although the element is  
 775 called “Rate”, if average membrane potential has been chosen as the activity of this population, this is what  
 776 will be recorded here. *<Density>* is used to record the full probability density of the given population node.  
 777 As density is only relevant for the population density technique, it can only be recorded from nodes which  
 778 instantiate the mesh or grid algorithm types. The attributes are the node *name*, *t\_start*, *t\_end*, and *t\_interval*  
 779 which define the simulation times to start and end recording the density at the given interval. A file which  
 780 holds the probability mass values for each cell in the mesh or grid will be created in the output directory  
 781 for each *t\_interval* between *t\_start* and *t\_end*. Finally, the *<Display>* element can be used to observe the  
 782 evolution of the probability density function as the simulation is running. If a *Display* element is added in  
 783 the XML file for a specific node, when the simulation is run, a graphical window will open and display the  
 784 probability density for each time step. Again, display is only applicable to algorithms involving densities.  
 785 Enabling the display can significantly slow the simulation down. However, it is useful for debugging the  
 786 simulation and furthermore, each displayed frame is stored in the output directory so that a movie can be  
 787 made of the node’s behaviour. How to generate this movie is discussed later in section 7.1.

**Listing 21.** A set of reporting definitions to record the probability densities and rates of two populations, S and D. The densities will also be displayed during simulation.

```
788 <Reporting>
789 ...
790   <Density node="S" t_start="0.0" t_end="6.0" t_interval="0.01" />
791   <Density node="D" t_start="0.5" t_end="1.5" t_interval="0.001" />
792   <Display node="S" />
793   <Display node="D" />
794   <Rate node="S" t_interval="0.0001" />
795   <Rate node="D" t_interval="0.0001" />
796 ...
797 </Reporting>
```

#### 4.6 Variables

799 The *<Simulation>* element can contain multiple *<Variable>* sub-elements each with a unique name  
 800 and value. Variables are provided for the convenience of the user and can replace any values in the XML  
 801 file. For example, a variable named *TIME\_END* can be defined to replace the value in the *t\_end* element of  
 802 the *SimulationRunParameter* block. When the simulation is run, the value of *t\_end* will be replaced with  
 803 the default value provided in the Variable definition. Using variables makes it easy to perform parameter  
 804 sweeps where the same simulation is run multiple times and only the variable’s value is changed. How  
 805 parameter sweeps are performed is covered in the supplementary material section 8. All values in a MIIND

806 XML script can be set with a variable name. The type of the Variable is implicit and an error will be thrown  
 807 if, say, a non-numerical value is passed to the tau\_refractive attribute of a MeshAlgorithm object.

**Listing 22.** A Variable definition. TIME\_END has a default value of 18.0 and is used in the *t\_end* parameter definition.

```
808 <Variable Name='TIME_END'>18.0</Variable>
809 ...
810 <t_end>TIME_END</t_end>
```

## 5 MIIND ON THE GPU

811 The population density techniques of the mesh and grid algorithms rely on multiple applications of the  
 812 transition matrix which can be performed on each cell in parallel. This makes the algorithms prime  
 813 candidates for parallelisation on the graphics card. In the CPU versions, the probability mass is stored  
 814 in separate arrays, one for each population/node in the simulation. For the GPGPU version, these are  
 815 concatenated into one large probability mass vector so all cells in all populations can be processed in parallel.  
 816 From the user's perspective, switching between CPU and GPU implementations is trivial. In the XML file  
 817 for a simulation which uses MeshAlgorithm or GridAlgoirthm, to switch to the vectorised GPU version, the  
 818 Algorithm types must be changed to MeshAlgorithmGroup and GridAlgorithmGroup. All other attributes  
 819 remain the same. Only MeshAlgorithmGroup, GridAlgorithmGroup, and RateFunctor/RateAlgorithm  
 820 types can be used for a vectorised simulation. When running a MIIND simulation containing a group  
 821 algorithm from a Python script, instead of importing *miind.miindsim*, *miind.miindsimv* should be used. The  
 822 Python module *miind.run* is agnostic to the use of group algorithms so can be used as shown previously.

**Listing 23.** A MeshAlgorithmGroup definition is identical to a MeshAlgorithm definition except for the type.

```
823 <Algorithm type="MeshAlgorithmGroup" name="ALG_ADEX" modelfile="adex.model" >
824   <TimeStep>0.001</TimeStep>
825   <MatrixFile>adex_0.05_0_0_0_.mat</MatrixFile>
826   <MatrixFile>adex_-0.05_0_0_0_.mat</MatrixFile>
827 </Algorithm>
828 <Algorithm type="GridAlgorithmGroup" name="OSC" modelfile="fn.model" tau_refractive="0.0" transformfile=
829   ↳ "fn_0_0_0_0_.tmat" start_v="-1.0" start_w="-0.3" ratemethod="AvgV">
830   <TimeStep>0.00001</TimeStep>
831 </Algorithm>
```

832 The GPGPU implementation uses the Euler method to solve the master process during each iteration. It  
 833 is, therefore, susceptible to blow-up if the time step is large or if the local dynamics of the model are stiff.  
 834 The user has the option to set the number of euler steps taken each iteration using the *master\_steps* value of  
 835 the SimulationRunParameter block in the XML file. A higher value reduces the likelihood of blow-up but  
 836 increases the simulation time.

837 In order to run the vectorised simulations, MIIND must be running on a CUDA enabled machine and have  
 838 CUDA enabled in the installation (CUDA is supported in the Windows and Linux python installations).  
 839 Section 3 in the supplementary material goes into greater detail about the systems architecture differences  
 840 between the CPU and GPU versions of the MIIND code. Using the “Group” algorithms is recommended if  
 841 possible as it provides a significant performance increase. Benchmarking details for MIIND compared to  
 842 direct simulation are available in De Kamps et al. (2019).

## 6 RUNNING A MIIND SIMULATION IN PYTHON

843 As demonstrated in the quick start guide, the command `python -m miind.run` takes a simulation XML file  
 844 as a parameter and runs the simulation. A similar script may be written by the user to give more control  
 845 over what happens during a simulation and how output activity is recorded and processed. It even allows  
 846 MIIND simulations to be integrated into other Python applications such as the Virtual Brain (Sanz Leon  
 847 et al., 2013) so the population density technique can be used to solve the behaviour of nodes in a brain-scale  
 848 network (see section 9). To run a MIIND simulation in a Python script, the module `miind.miindsim` must be  
 849 imported (or `miind.miindsimv` if the simulation uses MeshAlgorithmGroup or GridAlgorithmGroup and  
 850 therefore requires CUDA support). Listing 24 shows an example script which uses the following available  
 851 functions to control the simulation.

**Listing 24.** A simple python script for running a MIIND simulation and plotting the results.

```
852 import matplotlib.pyplot as plt
853 import miind.miindsim as miind
854
855 miind.init(1, "lif.xml")
856
857 timestep = miind.getTimeStep()
858 simulation_length = miind.getSimulationLength()
859 print('Timestep from XML : {}'.format(timestep))
860 print('Sim time from XML : {}'.format(simulation_length))
861
862 miind.startSimulation()
863
864 constant_input = [2500]
865 activities = []
866 for i in range(int(simulation_length/timestep)):
867     activities.append(miind.evolveSingleStep(constant_input)[0])
868
869 miind.endSimulation()
870
871 plt.figure()
872 plt.plot(activities)
873 plt.title("Firing Rate.")
874
875 plt.show()
```

### 876 6.1 init(node\_count,simulation\_xml\_file,...)

877 The `init` function should be called first once the MIIND library has been imported. This sets up the  
 878 simulation ready to be started. The `node_count` parameter allows for multiple instantiations of the simulation  
 879 to be run simultaneously. The Nodes, Connections, and Reporting blocks from the simulation file will be  
 880 duplicated, effectively running the same model `node_count` times simultaneously in the same simulation.  
 881 This functionality was included to allow the Virtual Brain to run the simulation defined in the XML file  
 882 multiple times (see section 9). The `simulation_xml_file` parameter gives the name of the simulation xml file  
 883 to be run. If the file has any variables defined, these are made available in Python as additional parameters  
 884 to the `init` function. In this way, the use of XML variables can be used for parameter sweeps. All variables  
 885 must be passed as strings. If a variable is not set in the call to `init`, the default value defined in the XML file  
 886 will be used.

**Listing 25.** Calling init for a MIIND simulation lif.xml with the Variable SIM\_TIME set to 0.4.

```
887 miind.init(1, "lif.xml", SIM_TIME="0.4")
```

## 888 6.2 **getTimeStep() and getSimulationLength()**

889 Once *init* has been called, the functions *getTimeStep* and *getSimulationLength* can be used to extract the  
 890 time step and simulation length in seconds from the simulation respectively. The Python script controls  
 891 when each iteration of the MIIND simulation is called and so it needs to know the total number of iterations  
 892 to make. Furthermore, it can be useful for integration with other systems to know these values.

## 893 6.3 **startSimulation()**

894 *startSimulation* indicates in the Python script that the simulation should be initialised ready for the  
 895 simulation loop to be called.

## 896 6.4 **evolveSingleStep(input)**

897 By calling *evolveSingleStep* in the Python script, the MIIND simulation will move forward one time step.  
 898 This function takes a list of numbers as a parameter. The list corresponds to inputs to the population nodes  
 899 in the MIIND simulation. In this way, the user may control the behaviour of the simulation from the Python  
 900 script during the simulation. The *evolveSingleStep* function also returns a list of numbers which are the  
 901 output activities of the population nodes. Section 6.6 provides more information about how to use the input  
 902 and output of this function. *evolveSingleStep* should be called in a loop which will run the same number of  
 903 iterations as would be expected if the XML file were run in MIIND directly, that is, the simulation length  
 904 divided by the time step.

## 905 6.5 **endSimulation()**

906 It is good practice to call *endSimulation* once all iterations of the simulation have been performed. This  
 907 allows MIIND to clean up and to print the performance statistics to the console.

## 908 6.6 **Additional XML Code for Python Support**

909 Although it is still possible to use *RateFunctor* or *RateAlgorithm* to set input rates to populations in a  
 910 Python MIIND simulation, *evolveSingleStep()* provides a means to pass the input rates as a parameter so  
 911 that more complex input patterns can be used. In order to indicate that a population will receive input  
 912 externally from the Python script (via the list input to *evolveSingleStep()*) a special connection type must  
 913 be defined in the *<Connections>* section of the XML.

### **Listing 26.** Special connection types for use in Python.

```
914 <Connections>
915 ...
916 <IncomingConnection Node="E">1 0.01 0</IncomingConnection>
917 <OutgoingConnection Node="E"/>
918 ...
919 </Connections>
```

920 Listing 26 defines an input to node E which will be interpreted as a *DelayedConnection* with the number  
 921 of connections equal to 1 and a post synaptic efficacy of 0.01. No delay is defined here although it is  
 922 permitted. *OutgoingConnections* are used to declare which nodes in the population network will pass their  
 923 activity back to the Python script after each iteration. If the two connections in the listing are the only  
 924 instances of *IncomingConnection* and *OutgoingConnection*, then the *evolveSingleStep* function will expect  
 925 as a parameter, a list with one numeric value to represent the incoming rate to node E. *evolveSingleStep*  
 926 will return a list with a single numeric value representing the activity of node E. In cases where there are  
 927 more than one *IncomingConnection*, the order of values in the Python list parameter to *evolveSingleStep* is  
 928 the same as the order of *IncomingConnections* defined in the XML. Similarly with *OutgoingConnections*,

929 the order of the list of activities returned from *evolveSingleStep* is the same as the order of declaration in  
930 the XML file.

## 7 USING THE CLI TO QUICKLY VIEW RESULTS

931 Once a simulation has been run, either using *miind.run* or from a user written Python script, the  
932 *miind.miindio* CLI can be used to quickly plot the recorded results. As mentioned, the commands used  
933 in *miindio* are based on the module *miind.miind\_api* and are reproducible in a Python script. However, it  
934 can be convenient to be able to run them directly from the command line to aid fast prototyping and bug  
935 fixing of models and simulations. The following section lists some common commands in the CLI and  
936 their usage. The accompanying files for this example are in the *examples/cli\_plots* directory. The following  
937 command starts the CLI and presets the user with a prompt:

### **Listing 27.** Run the CLI.

938 `$ python -m miind.miindio`

939 When *miind.miindio* is called for the first time in a working directory, the user must identify the XML file  
940 which will describe the current working simulation. MIIND stores a reference to this file in a settings file in  
941 the working directory so that all subsequent commands will reference this simulation. Even if *miind.miindio*  
942 is quit and restarted, the current working simulation will be used as the context for commands until a new  
943 current working simulation is defined or if it is called in a different directory. The user can set the current  
944 working simulation with the **sim** command.

### **Listing 28.** Load a simulation file in the CLI.

945 `> sim example.xml`

946 Calling **sim** without a parameter will list information about the current working simulation such as the  
947 output directory, XML file name and provide a list of the defined variables and nodes.

948 During the simulation, MIIND generates output files according to the requirements of the *<Recording>*  
949 object of the XML file which could include the average firing rate of population nodes or their densities at  
950 each time interval. The average firing rate can be plotted from the CLI using the **rate** command followed by  
951 the name of the population node. To be reminded of the node names, the user can call **sim** or **rate** without  
952 parameters.

### **Listing 29.** Plot the rate of population POP1 in the CLI.

953 `> rate POP1`

954 Even while a simulation is running, calling **rate** in the CLI will plot the recorded activity up to the latest  
955 simulated time point. This is useful to keep an eye on the simulation as it progresses without waiting for  
956 completion. An example of the plots produced by **rate** is shown in Fig. 11A.

957 For populations using the grid or mesh algorithms, the user can call the **plot-density** command with  
958 parameters identifying the required node name and simulation time.

### **Listing 30.** Plot the probability density of population POP1 at time 0.42s in the CLI.

959 `> plot-density POP1 0.42`

960 This command renders the mesh or grid and its population density at the given simulation time. When  
961 reading the simulation time parameter in the command, MIIND expects the time to be an integer multiple  
962 of the time step and to be expressed up to its least significant figure (for example, 0.1 instead of 0.10).

963 Again, this command can be run during a simulation providing the time has been simulated. An example of  
 964 a density plot is shown in Fig. 11B.

965 Similar to **plot-density**, **plot-marginals** can be used to display the marginal densities of a given population  
 966 at a given time. Both marginals are plotted next to each other. The details of how marginal densities are  
 967 calculated are explained in the supplementary material section 5. Fig. 11C shows an example of a marginal  
 968 density plot.

**Listing 31.** Plot the marginal distributions of population POP1 at time 0.42s in the CLI.

969 > plot-marginals POP1 0.42

## 970 7.1 Generate a Density Movie

971 If, in the XML file *<Recording>* section, the *<Display>* element is added for a given population, the  
 972 output directory will be populated with still images of density plots at each time step. Once the simulation  
 973 is complete, calling **generate-density-movie** in the CLI will produce an MP4 movie file made from the  
 974 still images. The parameters are the node name followed by the size of the square video frame in pixels.  
 975 The third parameter is the desired time to display each image (every time step of the simulation) in seconds.  
 976 If the video should be the same length as the simulation time, then this parameter should match the time  
 977 step of the simulation. By changing the value, the video time can be altered. For example, if the parameter  
 978 is set to 0.01 for a simulation with time step 0.001, then the video length will be 10 times the length of the  
 979 simulation. Finally, a name for the video file must be given.

**Listing 32.** Generate a movie from the display images of population POP1 with a size of 512 pixels at a  
 simulation replay time step of 0.1s.

980 > generate-density-movie POP1 512 0.1 pop1\_mov

981 The movie file will be created in the working directory of the simulation. A movie of the marginal density  
 982 plots can also be created using the **generate-marginal-movie** command which takes the same parameters.  
 983 As each marginal plot must be generated from the density output, this takes a considerably longer time  
 984 than for the density movie.

**Listing 33.** Generate a marginals movie from the density files of population POP1 with a size of 512  
 pixels at a simulation replay time step of 0.1s.

985 > generate-marginal-movie POP1 512 0.1 pop1\_marginal\_mov

## 8 DESCRIPTION OF MIIND'S ARCHITECTURE AND FUNCTIONALITY

986 The main architectural concerns in MIIND relate to the two C++ libraries, MPILib and TwoDLib. MPILib  
 987 is responsible for instantiating and running the simulation. TwoDLib contains the CPU implementations of  
 988 the grid and mesh algorithms. It is also responsible for generating transition matrices. Of the remaining  
 989 libraries, GeomLib contains a population density technique implementation of neuron models with one  
 990 time dependent variable, although it is also possible and indeed preferable to use the TwoDLib code for  
 991 one dimensional models. EPFLLib and NumtoolsLib contain helper classes and type definitions. Fig. 12  
 992 shows a reduced UML diagram of the MIIND C++ architecture. The aim of this section is to give a brief  
 993 overview of the C++ MIIND code as a starting point for developers. The CUDA implementation of MIIND  
 994 is similar in structure to the CPU solution and is available in the CudaTwoDLib and MiindLib libraries. A  
 995 description of the differences is given in section 3 of the supplementary material.

---

**996 8.1 MPILib**

997 The MPINetwork class in MPILib represents a simulation as a whole and is instantiated in the *init* function  
998 of the SimulationParserCPU class which is a specialisation of MiindTvbModelAbstract. *init* is called from  
999 the Python module and, as the name suggests, MiindTvbModelAbstract was originally written with the aim  
1000 of Python integration into TVB. MPINetwork exposes member functions for building a network of nodes  
1001 where each node is an instance of a neuron population which can be connected together so that the output  
1002 activity from one population is input to another. The class also contains all of the simulation parameters  
1003 such as the simulation length and time step. Finally, the MPINetwork class exposes a function to run the  
1004 simulation in its entirety or take a single evolve step for use in an external control loop.

1005 Each node in the population network is represented by an instance of the MPINode class. A node  
1006 has a name and an ID which is used to uniquely identify it in the simulation. A node also contains an  
1007 implementation of AlgorithmInterface performing the integration technique required for this population  
1008 (for example, GridAlgorithm or MeshAlgorithm). The *NodeType* describes whether a population should be  
1009 thought of as excitatory or inhibitory. As discussed earlier, MIIND performs a validation check that the  
1010 synaptic efficacy from a node is positive or negative respectively (or neutral). During each iteration, each  
1011 node is responsible for consolidating the activity of all input connections, calling the integration step in the  
1012 AlgorithmInterface implementation, and reporting the density and output activity (the average firing rate or  
1013 membrane potential).

1014 In MPILib, a number of implementations of AlgorithmInterface are defined which can be instantiated  
1015 in a node. Implementations of AlgorithmInterface are responsible for the lion's share of the computation  
1016 in MIIND as this is where the integration of the model is performed. The interface is extremely simple,  
1017 providing a function to set parameters, an optional function for a preamble before each iteration, and  
1018 the *evolveNodeState* function to be called every time step. GridAlgorithm and MeshAlgorithm are imple-  
1019 mentations of this interface defined in TwoDLib. MPILib and GeomLib hold the implementations of the  
1020 remaining algorithms available to the user which were discussed in section 4. Finally, the weight types,  
1021 DelayedConnection and CustomConnectionParameters are also defined in MPILib. All classes are C++  
1022 templates which take the weight type as a parameter to avoid code duplication and to enforce that only  
1023 algorithms with the same weight type can be used together.

**1024 8.2 TwoDLib**

1025 As with the population models in MPILib and GeomLib, GridAlgorithm and MeshAlgorithm are  
1026 implementations of the AlgorithmInterface. We will focus here on the grid algorithm implementation  
1027 although the mesh algorithm uses the same structures or specialisations of those structures to perform  
1028 similar tasks as set out in section 3. GridAlgorithm is supported by two important classes. **Ode2DSys-  
1029 tem** transfers probability mass according to the reset mapping of the *.model* file and calculates the average firing  
1030 rate of the population. In MeshAlgorithm, Ode2DSys-tem also performs the pointer update for shifting  
1031 probability mass down the strips of the mesh. **MasterGrid** is responsible for solving the Poisson master  
1032 equation using a transition matrix calculated at simulation time based on the desired efficacy and grid  
1033 cell size. For each iteration, the function *evolveNodeState* is called which performs the main steps of the  
1034 population density algorithm.

1035 First, in GridAlgorithm, the deterministic dynamics are solved by applying the pre-generated transition  
1036 matrix once. The second step is a call to *Ode2DSys-tem.RedistributeProbability()* to perform any reset  
1037 mappings for probability mass which appeared in the threshold cells last iteration. This step is useful for  
1038 neuron models, such as leaky integrate and fire, which contain an instruction to reset one or more variables  
1039 to a different value upon reaching a threshold.

1040 The third step calls on the MasterGrid class to solve the master equation for the incoming Poisson spike  
1041 rates from every incident node. MasterGrid begins with the current state of the probability mass distribution  
1042 across the grid, that is, the probability mass values of each cell in the grid. As described in section 2, every  
1043 cell has the same relative transition of probability mass due to a single incoming spike. For the whole  
1044 grid, this single transition is duplicated into a transition matrix which can be applied to the full probability  
1045 mass vector. Because there are at most two cells into which probability mass is transferred, this matrix  
1046 is extremely sparse and can be stored efficiently in a compressed sparse row (CSR) matrix. In the mesh  
1047 algorithm, this matrix is loaded from the .mat file.

1048 MeshAlgorithm requires a fourth step to transfer probability mass from the ends of strips to stationary  
1049 cells subject to a reversal mapping generated during the pre-processing phase. This is discussed in the  
1050 supplementary material section 6.

1051 Finally, SimulationParserCPU is an extension of the MiindTvbModelAbstract class used to parse the  
1052 simulation XML file and instantiate an MPINetwork object with the appropriate nodes and connections. Its  
1053 extensions of the functions declared in MiindTvbModelAbstract are exposed to the Python module to be  
1054 called from a Python script.

## 9 DISCUSSION

### 1055 MIIND fulfills a need for insight into neural behaviour at mesoscopic scales.

1056 The MIIND population density technique allows researchers to simulate population level behaviour by  
1057 defining the behaviour of the underlying neurons. This is in contrast to many rate based models which  
1058 describe the population behaviour directly. An example of how population behaviour can differ from the  
1059 underlying neuron model can be seen in the behaviour of a population of bursting neurons such as the  
1060 Izhikevich simple model. A single Izhikevich neuron with a constant input current or input spike rate  
1061 oscillates between a bursting period of repeated firing and a quiescent period of no firing. The average  
1062 behaviour of a population of Izhikevich neurons is different. Initially, all neurons are synchronised, they  
1063 burst and quiesce at the same time producing an oscillatory pattern of average firing rate in the population.  
1064 However, due to the random nature of Poisson input spikes, the neurons de-synchronise over time and the  
1065 average firing rate of the whole population damps to a constant value because only a subset of neurons  
1066 are bursting at any one time. Fig. 11A shows the damping of the output firing rate oscillations and the  
1067 ‘desynchronised’ density of a population of Izhikevich simple neurons.

### 1068 TVB Integration

1069 The Virtual Brain (Sanz Leon et al., 2013) and MIIND are both systems which facilitate the development  
1070 of neural mass or mean field population models with explicit descriptions of how multiple populations are  
1071 connected. Using these systems, the complex dynamics arising from the interaction of populations can be  
1072 studied. TVB provides a framework to describe a network of nodes (the connectivity) which, while it can be  
1073 abstract, generally represents regions of the human or primate brain. Connections between nodes represent  
1074 white matter tracts which transfer signals from one node to the next based on length and propagation speed.  
1075 TVB also allows the description of “coupling” functions which modulate these signals as they pass from  
1076 one node to another. Typically, the number of nodes is in the order of 100 or so. However, TVB also allows  
1077 for the definition of a “surface” which can be associated with 10s of thousands of nodes to simulate output  
1078 from common medical recording techniques such as EEG and BOLD fMRI. TVB has impressive clinical  
1079 relevance as well as supporting more theoretical neuroscience research. Users can build simulations using  
1080 the graphical user interface or directly using the Python source code.

1081 While MIIND and TVB have many functional similarities, both have differing strengths with respect to  
1082 the underlying simulation techniques and surrounding infrastructure. It was therefore clear that integrating  
1083 the smaller system, MIIND, into the more developed infrastructure of TVB might yield benefits from both.

1084 Although it is possible to model delayed connections and synaptic dynamics between populations in  
1085 MIIND, TVB provides a comprehensive method of defining such structures and behaviours through the  
1086 connectivity network and coupling functions. Some users of MIIND may find it useful and appropriate to  
1087 house their simulations in such a structure.

1088 TVB uses a number of model classes to describe the behaviour of the nodes in a network. When the  
1089 simulation is run, an instantiation of a specified model class takes the signals which have passed through  
1090 the network to arrive at each node and integrates forward by one time step (depending on the integration  
1091 method). In order to use MIIND nodes in TVB, a specialised model class was created to import the MIIND  
1092 Python library, instantiate it, then make a call to *evolveSingleStep()* in place of the integration function. The  
1093 inputs and outputs of *evolveSingleStep()* are treated by TVB as any other model. As the MIIND Python  
1094 library takes a simulation file name as a parameter to its *init* function, a single additional model class is all  
1095 that is required to expose any MIIND simulation to TVB. Fig. 13 shows the results from a simulation of  
1096 the TVB default whole-brain connectivity with populations of Izhikevich simple neurons in MIIND. The  
1097 script and simulation files are available in the *examples/miind\_tvb* directory of the MIIND repository. Both  
1098 TVB and MIIND must be installed to sucessfully run the example.

### 1099 **Reasoning about probability density instead of populations of individual neurons 1100 simplifies output analysis.**

1101 The output firing rate or membrane potential of a MIIND population which uses the the mesh algorithm  
1102 or grid algorithm is devoid of any variation which you would see from a population of individual neurons.  
1103 This is because the effect of Poisson generated input spike trains is applied to a probability density function,  
1104 effectively an infinite population of neurons. Spike train inputs to a finite population of neurons produces  
1105 variation in how individual neurons move through state space resulting in noisy output rates at the population  
1106 level. While this can be mitigated using a larger number of neurons, the use of smoothing techniques, or  
1107 curve fitting, MIIND requires none of these methods to produce an output which is immediately clear to  
1108 interpret. For example, MIIND was used to build and simulate a spinal circuit model using populations  
1109 of integrate and fire neurons (York et al., 2019). The average firing rates of the populations were used to  
1110 compare patterns of activity with results from an EMG experiment. As the patterns to be observed were  
1111 on the order of seconds, there was no need to capture faster variation in activity from the simulation and  
1112 indeed, a direct simulation would have produced output which may have obscured these patterns.

1113 MIIND has also been used to simulate central pattern generator models which rely on mutually inhibiting  
1114 populations of bursting neurons. The interaction of the two populations significantly influences their sub-  
1115 threshold dynamics. In particular, it can be difficult to identify the dynamics responsible for the swapping  
1116 of states from bursting to quiescent (escape or release). Observing the changing probability density function  
1117 during the simulation makes it very clear how the two populations are behaving.

### 1118 **Handling Noise**

1119 A major benefit of MIIND's population density technique is the ability to observe the effect of noise on a  
1120 population, and to manipulate noise in an intuitive way. For a given simulation, the Poisson distributed  
1121 input to a population causes a spread of probability mass across the state space as some neurons receive  
1122 many spikes, and some receive fewer. It is explained in de Kamps (2013) how the Poisson input causes a  
1123 mean increase in membrane potential equal to the product of the post synaptic efficacy,  $h$ , and the average

1124 input rate,  $\nu$ . It causes a variance equal to  $\nu h^2$ .  $h$  and  $\nu$  can therefore be set such that the mean remains the  
1125 same but the variance changes to observe the effect of noise on the population.

1126 Another simple way to increase the variance of the population is to introduce two additional inputs with  
1127 equal rates and opposite post-synaptic efficacies. Again, the mean increase caused by the input remains  
1128 unchanged but the variance can be increased significantly and this requires only a small change to the XML  
1129 simulation file.

1130

### 1131 **A model agnostic system at the population level makes prototyping quick and intuitive.**

1132 Because MIIND provides insight of how a neuron model produces behaviour at the population level, it is  
1133 beneficial that the grid algorithm enables the user to quickly reproduce the *.model* and *.tmat* files if the  
1134 underlying neuron model needs to be changed. An example of this can be observed in a half-centre oscillator  
1135 made of a pair of mutually inhibiting populations of bursting neurons. The frequency of oscillation can be  
1136 made dependent or independent of the input spike rate by including a limit on the slow excitability variable  
1137 of the underlying neuron model. To make this change, the user can alter the neuron model then rebuild the  
1138 *.model* and *.tmat* file and no change to the population level network is required.

1139

### 1140 **DiPDE**

1141 DiPDE (DiPDE, 2015; Iyer et al., 2013) is an alternative implementation of the population density  
1142 technique for one dimensional neuron models. It does not employ the “mesh” discretisation method used  
1143 in the MIIND mesh algorithm and has primarily been used with populations of leaky integrate and fire  
1144 neurons. DiPDE can be used to simulate the Potjans-Diesmann microcircuit model (Cain et al., 2016)  
1145 which shows good agreement with MIIND (Fig. 5). MIIND is a much larger application than DiPDE  
1146 because it allows users to design their own underlying neuron models for each population using either the  
1147 mesh or grid algorithms.

1148

### 1149 **Future Work**

1150 A limitation on the MIIND population density technique is that a maximum of two time-dependent  
1151 variables can be used to describe the underlying neuron model of each population. In the mesh algorithm,  
1152 for higher dimensions, mesh building would need to be automated but this is not a trivial problem to solve.  
1153 The grid algorithm, however, is entirely automated and work has been done to extend MIIND for 3D  
1154 neuron models. Fig. 14 shows the 3D density plot of a population of Hindmarsh-Rose neurons in MIIND.  
1155 The technique used to generate the 2D transition matrices outlined in section 2 extends to N dimensions so  
1156 there is theoretically no limit to the dimensionality of the underlying neuron model in the grid algorithm.  
1157 However, both the grid algorithm and mesh algorithm suffer from “the curse of dimensionality” such that  
1158 with each additional variable, the number of cells to cover the state space increases to the point where the  
1159 memory and processing requirements are too high. Luckily, a great number of neuron behaviours can be  
1160 captured with only two or three time-dependent variables with appropriate approximations.

1161 Large networks can be built up quickly in MIIND. To add a node to a simulation file requires just a single  
1162 line. Integrating the node into the rest of the network with requisite connections is equally convenient. As  
1163 mentioned, the Potjans-Diesmann model has been implemented as a single cortical column but this is by  
1164 no means the limit of the size of network which can be built. It is feasible that a patch of cortex made of  
1165 perhaps hundreds of cortical columns can be simulated efficiently in MIIND. The benefit of such a network  
1166 would be to demonstrate how cortical columns interact together under different connectivity regimes and  
1167 inputs as well as providing the ability to quickly and easily “swap out” the underlying neuron model of

1168 each population. Typically, LIF is used but adaptive integrate and fire would be a closer approximation to  
1169 pyramidal neurons in cortex.

## 1170 Conclusion

1171 We have reintroduced MIIND's population density techniques for simulating populations of neurons  
1172 and given a full account of the features available to users. While the mesh algorithm was developed some  
1173 time ago, the grid algorithm which was added to MIIND recently has precipitated a more accessible, user  
1174 friendly software package. We hope that the explanations given here along with a lower technical barrier to  
1175 entry will encourage researchers to make use of the tool.

## CONFLICT OF INTEREST STATEMENT

1176 The authors declare that the research was conducted in the absence of any commercial or financial  
1177 relationships that could be construed as a potential conflict of interest.

## AUTHOR CONTRIBUTIONS

1178 HO and MdK contributed to the text of this article. YML, MEL, DS, and LD contributed to the development  
1179 of the population density technique and MIIND software.

## FUNDING

1180 This project received funding from the European Union's Horizon 2020 research and innovation programme  
1181 under Grant Agreement No. 720270 (HBP SGA1) and Specific Grant Agreement No. 785907 (Human  
1182 Brain Project SGA2) (MdK; YML). HO is funded by EPSRC. The funders had no role in study design,  
1183 data collection and analysis, decision to publish, or preparation of the manuscript.

## ACKNOWLEDGMENTS

1184 The authors wish to thank Frank van der Velde and Martin Perez-Guevara for their continued support of  
1185 the MIIND project.

## DATA AVAILABILITY STATEMENT

1186 The MIIND source code and installation packages are available as a github repository at <https://github.com/dekamps/miind>.

1188 MIIND can be installed for use in Python using “pip install miind” on many Linux, MacOS, and Windows  
1189 machines with python versions  $\geq 3.6$ .

1190 Documentation is available at <https://miind.readthedocs.io/>.

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## TABLES

**Table 1.** Parameters for the `grid_generate.generate` function.

Parameter Name	Notes
<code>func</code>	The underlying neuron model function.
<code>timestep</code>	The desired time step for the neuron model
<code>timescale</code>	A scale factor for the timescale of the underlying neuron model to convert the time step into seconds.
<code>tolerance</code>	An error tolerance for solving a single time step of the neuron model.
<code>basename</code>	The base name with which all output files will be named.
<code>threshold_v</code>	The spike threshold value for integrate and fire neuron models.
<code>reset_v</code>	The reset value for integrate and fire neuron models.
<code>reset_shift_h</code>	A value for increasing the second variable during reset for integrate and fire neuron models with some adaptive shift or similar function.
<code>grid_v_min</code>	The minimum value for the first dimension of the grid (usually membrane potential).
<code>grid_v_max</code>	The maximum value for the first dimension of the grid.
<code>grid_h_min</code>	The minimum value for the second dimension of the grid.
<code>grid_h_max</code>	The maximum value for the second dimension of the grid.
<code>grid_v_res</code>	The number of columns in the grid.
<code>grid_h_res</code>	The number of rows in the grid.
<code>efficacy_orientation</code>	The direction, ‘v’ or ‘h’, in which incoming spikes cause an instantaneous change.

**Table 2.** Parameters for the `generate-model` command in the CLI.

Parameter Name	Notes
<code>basename</code>	The shared name of the <code>.mesh</code> , <code>.stat</code> , <code>.rev</code> and generated <code>.model</code> files.
<code>reset</code>	The value (usually representing membrane potential) which probability mass will be transferred to having passed the threshold.
<code>threshold</code>	The value (usually representing membrane potential) beyond which probability mass will be transferred to the reset value.

**Table 3.** Parameters for the `generate-matrix` command in the CLI.

Parameter Name	Notes
<i>basename</i>	The shared name of the <code>.model</code> , <code>.fid</code> (if required), and generated <code>.mat</code> files.
<i>v_efficacy</i>	The efficacy value in the <i>v</i> (membrane potential) direction. If the parameter <i>h_efficacy</i> is used, this should be zero.
<i>points / precision</i>	For Monte Carlo, this gives the number of points per cell to use for approximating the transition matrix. For the geometric method, transitions are stored in the <code>.mat</code> file to the nearest $\frac{1}{precision}$
<i>h_efficacy</i>	The efficacy value in the <i>h</i> direction. If the parameter <i>v_efficacy</i> is used, this should be zero.
<i>reset-shift</i>	The shift in the <i>h</i> direction which neurons take when being reset.
<i>use_geometric</i>	A boolean flag set to “true” if the geometric method is used and “false” for Monte Carlo.

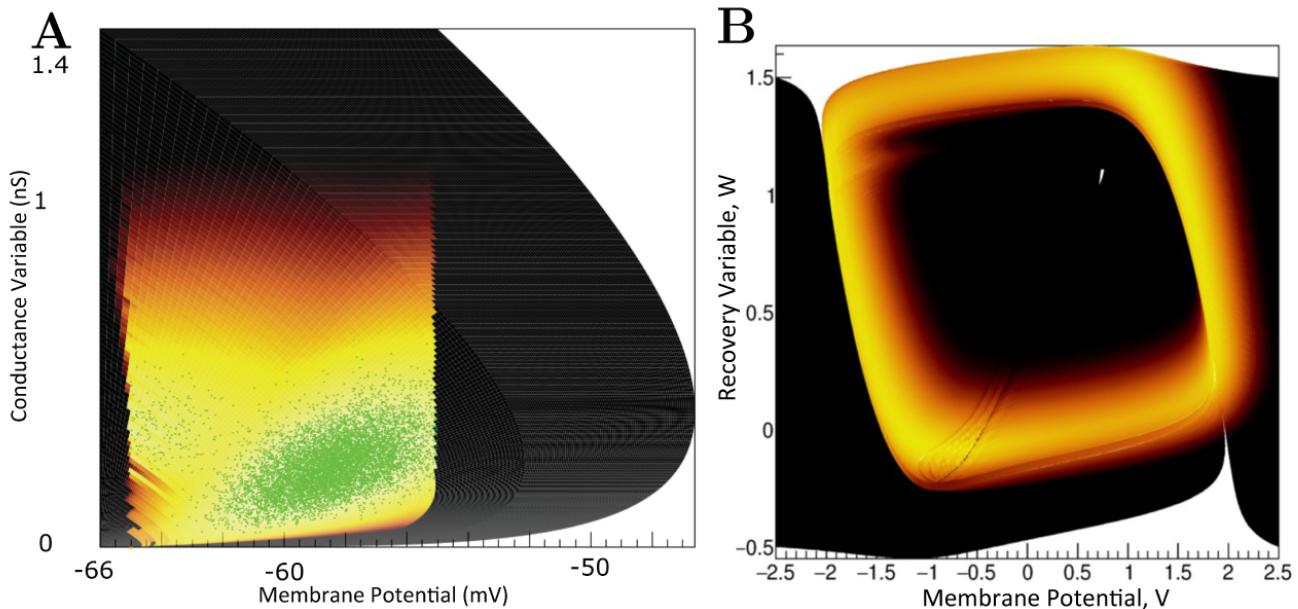
**Table 4.** Compatible weight types for each algorithm type defined in the simulation XML file.

Algorithm Name	double	DelayedConnection	CustomConnectionParameters
<i>RateAlgorithm</i>	✓	✓	✓
<i>MeshAlgorithm</i>		✓	
<i>MeshAlgorithmCustom</i>			✓
<i>GridAlgorithm</i>			✓
<i>GridJumpAlgorithm</i>			✓
<i>OUAlgorithm</i>		✓	✓
<i>WilsonCowanAlgorithm</i>	✓		
<i>RateFunctor</i>	✓	✓	✓

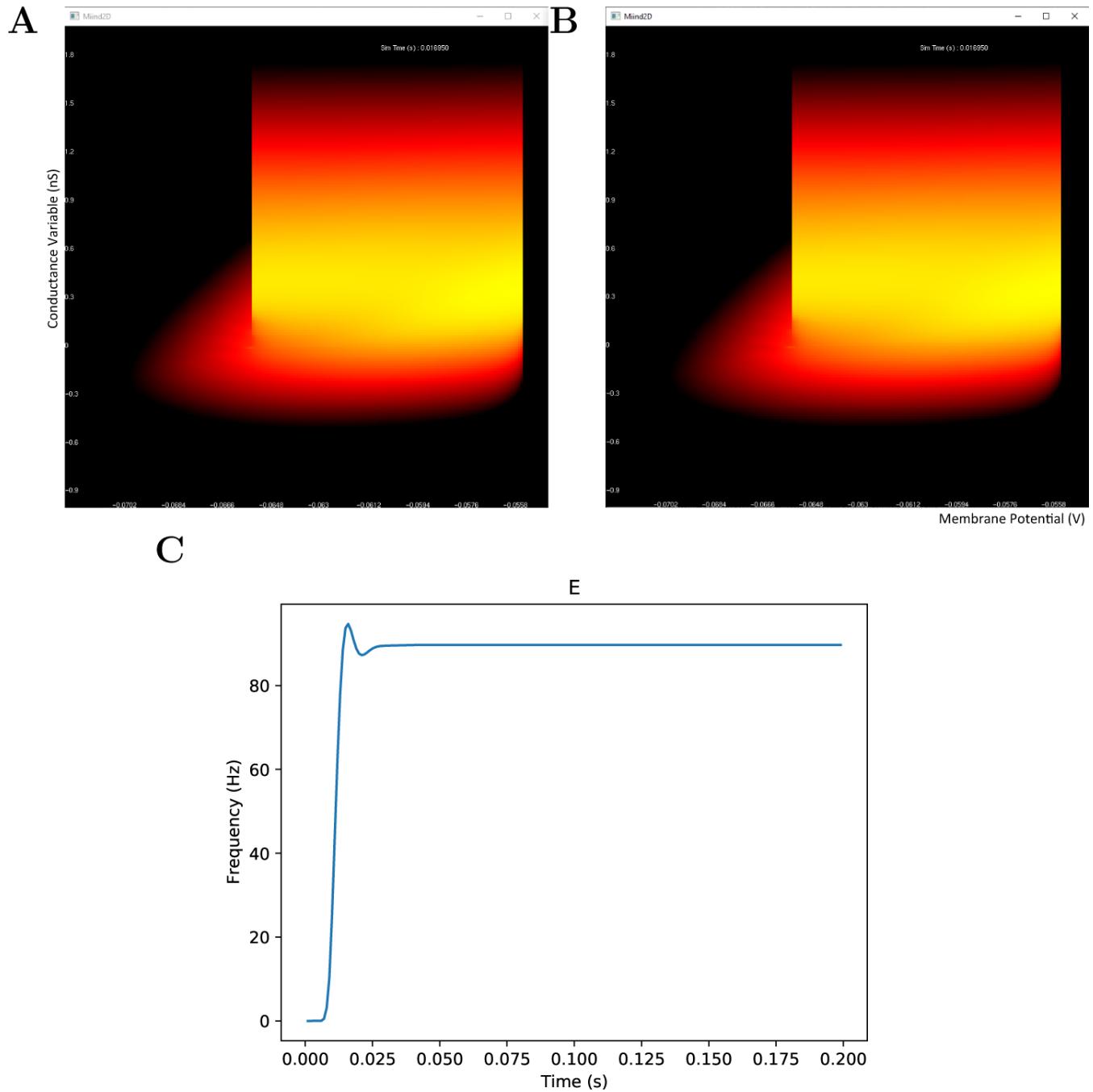
**Table 5.** The required sub-elements for the `SimulationRunParameter` section of the XML simulation file.

Element	Notes
<i>SimulationName</i>	The name of the simulation.
<i>t_end</i>	The simulation end time.
<i>t_step</i>	The time step of the simulation.
<i>name_log</i>	A file name for logging. The file is stored in the output directory of the simulation.
<i>master_steps</i>	The number of Euler iterations per time step used to solve the master equation in the GPGPU implementation.

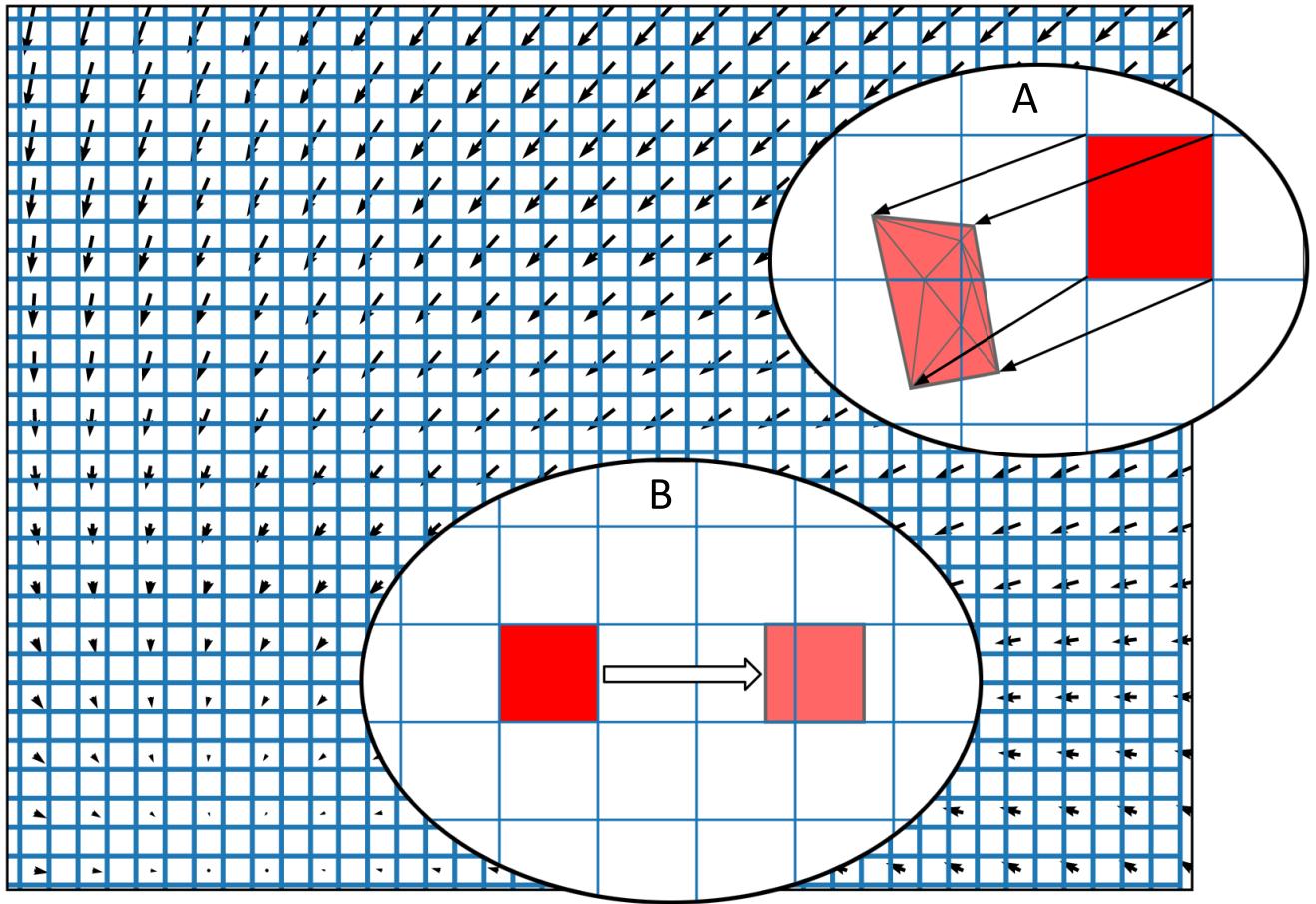
## FIGURES



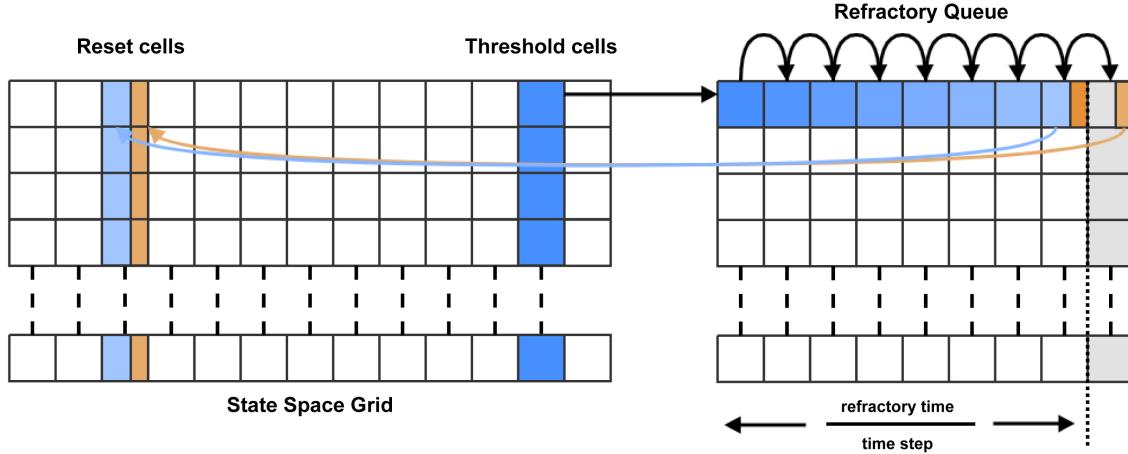
**Figure 1.** (A) The state space of a conductance based point model neuron. It is spanned by two variables: the membrane potential and a variable representing how open the channel is. This channel has an equilibrium potential that is positive. The green dots represent the state of individual neurons in a population. They are the result of the direct simulation of a group of neurons. MIIND, however, produces the heat plot representing a density which predicts where neurons in the population are likely to be: most likely in the white areas, least likely in the red areas and not at all in the black areas. The sharp vertical cut of the coloured area at -55mV represents the threshold at which neurons are removed from state space. They are subsequently inserted at the reset potential, at their original conductance state value. (B) The state space of a Fitzhugh-Nagumo neuron model. The axes have arbitrary units for variables  $V$  and  $W$ . There is no threshold-reset mechanism and the density follows a limit cycle. After a certain amount of simulation time, neurons can be found at all points along the limit cycle as shown here by a consistently high brightness.



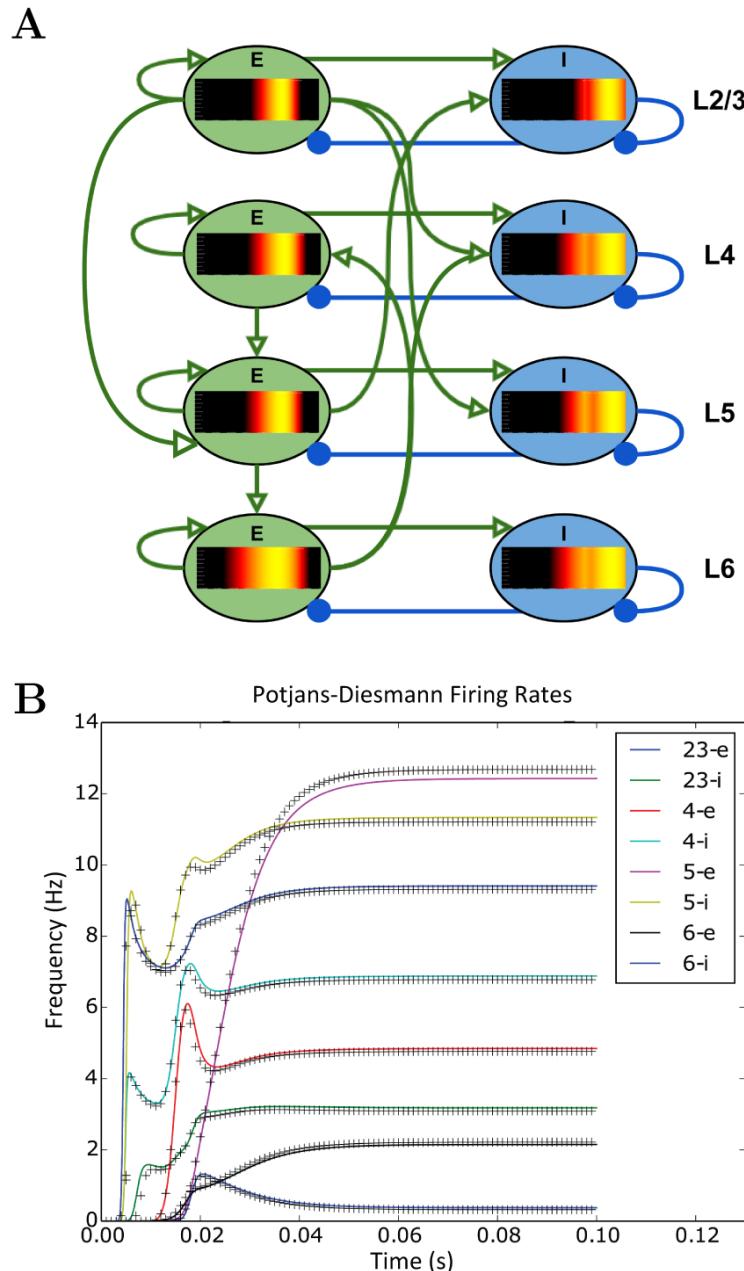
**Figure 2.** The display output of a running E-I population network simulation of conductance based neurons. (A) The probability density heat map of the excitatory population. (B) The probability density heat map of the inhibitory population. Brighter colours indicate a larger probability mass. The axes are unlabelled in the simulation windows as the software is agnostic to the underlying model. However, the membrane potential and conductance labels have been added for clarity. (C) The average firing rate of the excitatory population.



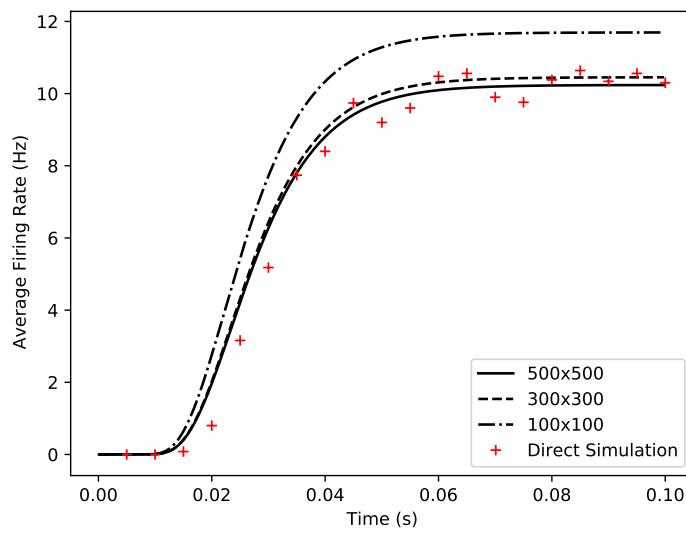
**Figure 3.** The state space of a neuron model (shown here as a vector field) is discretised into a regular grid of cells. (A) The transition matrix for solving the deterministic dynamics of the population is generated by applying a single time step of the underlying neuron model to each vertex of each cell in the grid and calculating the proportion by area to each overlapping cell. Once the vertices of a grid cell have been translated, the resulting polygon is recursively triangulated according to intersections with the original grid. Once complete, all triangles can be assigned to a cell and the area proportions can be summed. (B) For a single incoming spike (with constant efficacy), all cells are translated by the same amount and therefore have the same resulting transition which can be used to solve the Poisson master equation. In fact, the transition will always involve at most two target cells and the proportions can be calculated knowing only the grid cell width and the efficacy.



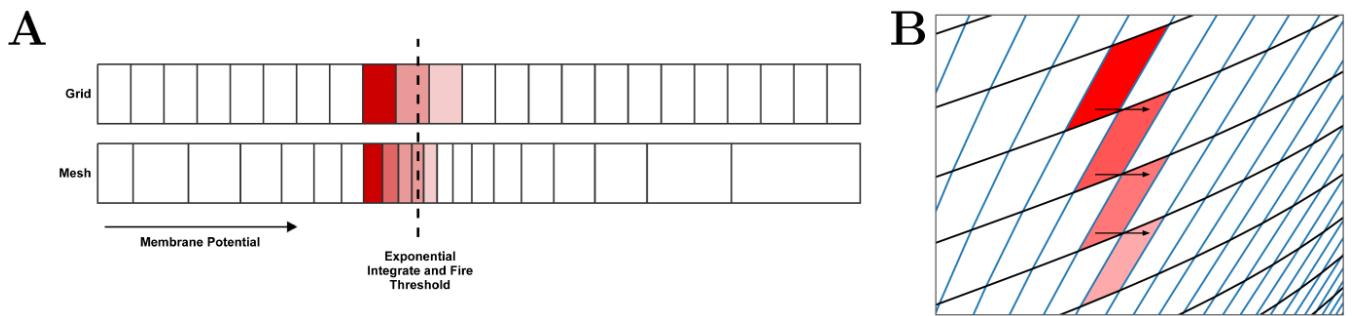
**Figure 4.** For each time step, probability mass in the cells which lie across the threshold (threshold cells) is pushed onto the beginning of the refractory queue. There is one queue per threshold cell. During each subsequent time step, the probability mass is shifted one place along the queue until it reaches the penultimate place. A proportion of the mass, calculated according to the modulo of the refractory time and the time step, is transferred to the appropriate reset cell. The remaining mass is shifted to the final place in the queue. During the next time step, that remaining mass is transferred to the reset cell.



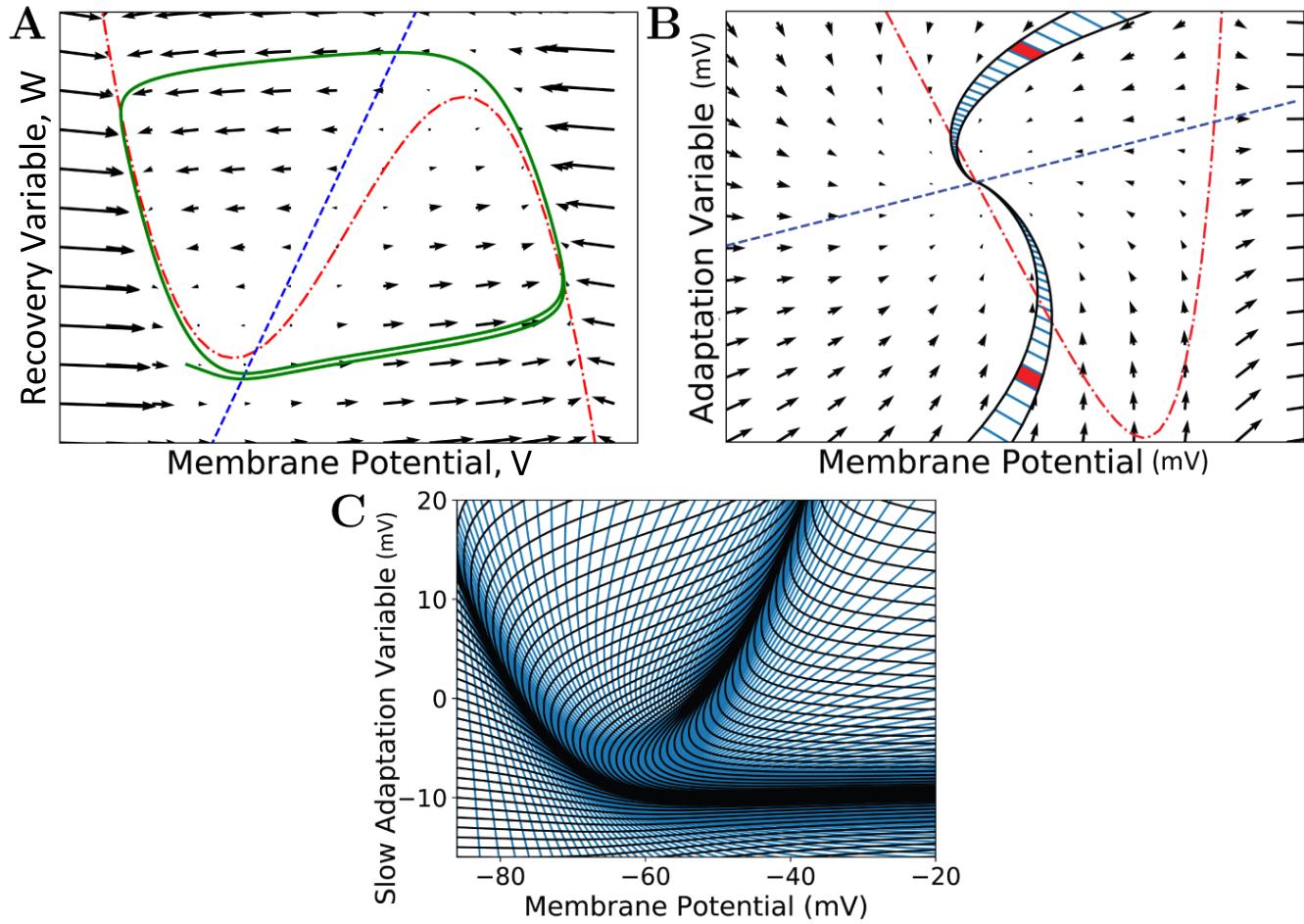
**Figure 5.** (A) A representation of the connectivity between populations in the Potjans-Diesmann microcircuit model. Each population shows the probability density at an early point in the simulation before all populations have reached a steady state. All populations are of leaky-integrate-and-fire neurons and so the density plots show membrane potential in the horizontal axis. The vertical axis has no meaning (probability mass values are the same at all points along the vertical). (B) The firing rate outputs from MIIND (crosses) in comparison to those from DiPDE for the same model (solid lines).



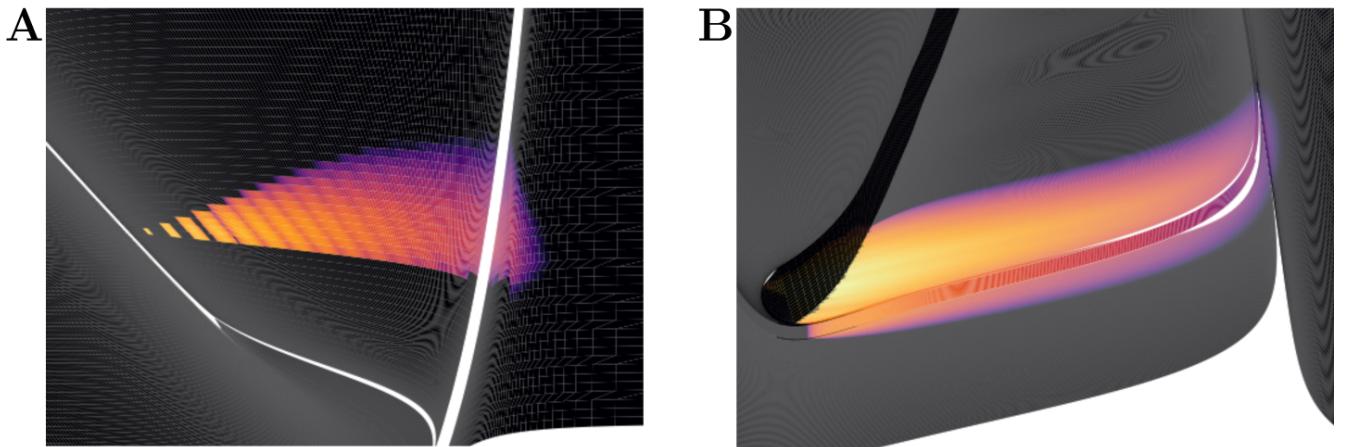
**Figure 6.** Comparison of average firing rates from four simulations of a single population of conductance based neurons. The black solid and dashed lines indicate MIIND simulations using the grid algorithm with different grid resolutions. The red crosses show the average firing rate of a direct simulation of 10,000 neurons.



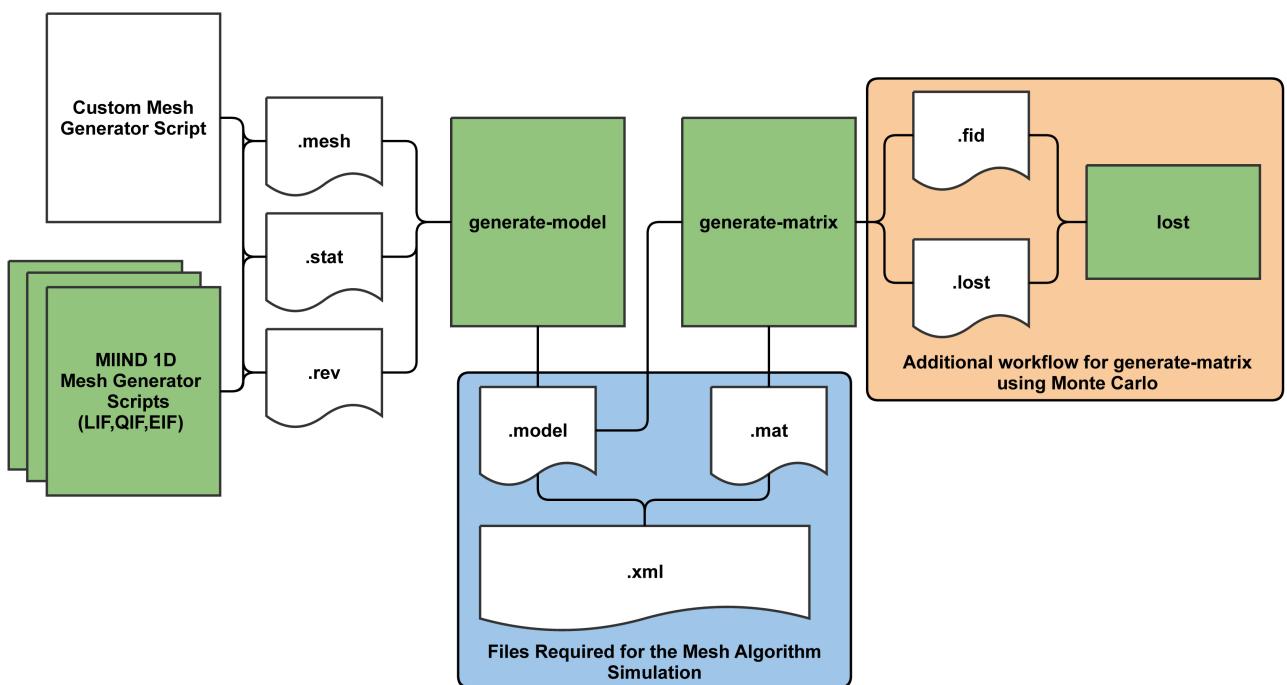
**Figure 7.** (A) In the grid algorithm, large cells cause probability mass to be distributed further than it should. This error is expressed most clearly in models where the the average firing rate of the population is highly dependent on the amount of probability mass passing through an area of slow dynamics. (B) In the mesh algorithm, when cells become shear, probability mass which is pushed to the right due to incoming spikes also moves laterally (downwards) because it is spread evenly across each cell.



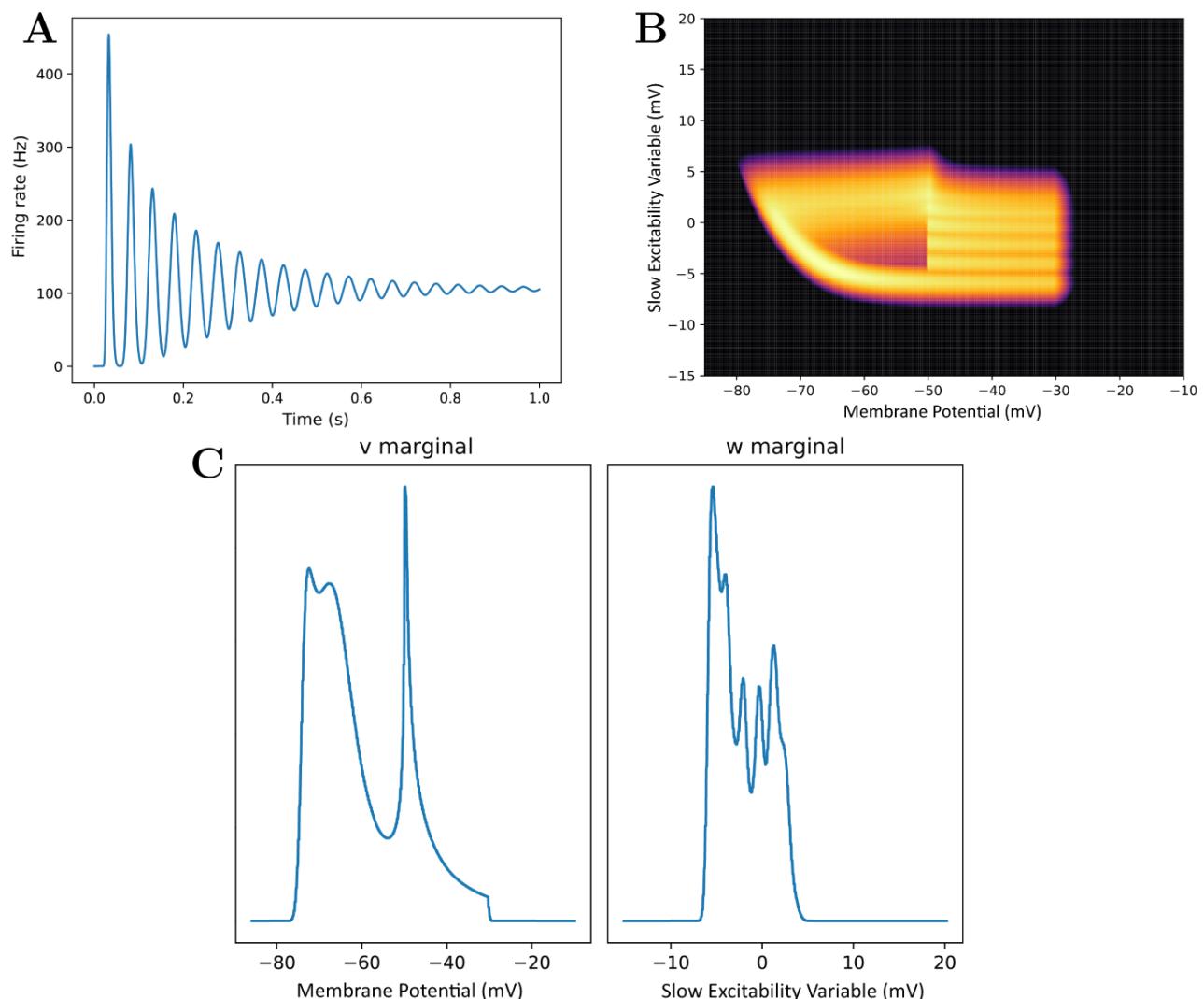
**Figure 8.** (A) A vector field of the FitzHugh-Nagumo neuron model (FitzHugh, 1961). Arrows show the direction of motion of states through the field according to the dynamics of the model. The red broken dashed nullcline indicates where the change in  $V$  is zero. The blue dashed nullcline indicates where the change in  $W$  is zero. The green solid line shows a potential path (trajectory) of a neuron in the state space. (B) A vector field for the adaptive exponential integrate and fire neuron model (Brette and Gerstner, 2005). Two strips are shown which follow the dynamics of the model and approach the stationary point where the nullclines cross. A strip is constructed between two trajectories in state space. Each time step of the two trajectories is used to segment the strip into cells. Because the strips approach a stationary point, they get thinner as the trajectories converge to the same point and cells get closer together as the distance in state space travelled reduces per time step (neurons slow down as they approach a stationary point). Per time step, probability mass is shifted from one cell to the next along the strip. (C) The state space of the Izhikevich simple neuron model (Izhikevich, 2003) which has been fully discretised into strips and cells.



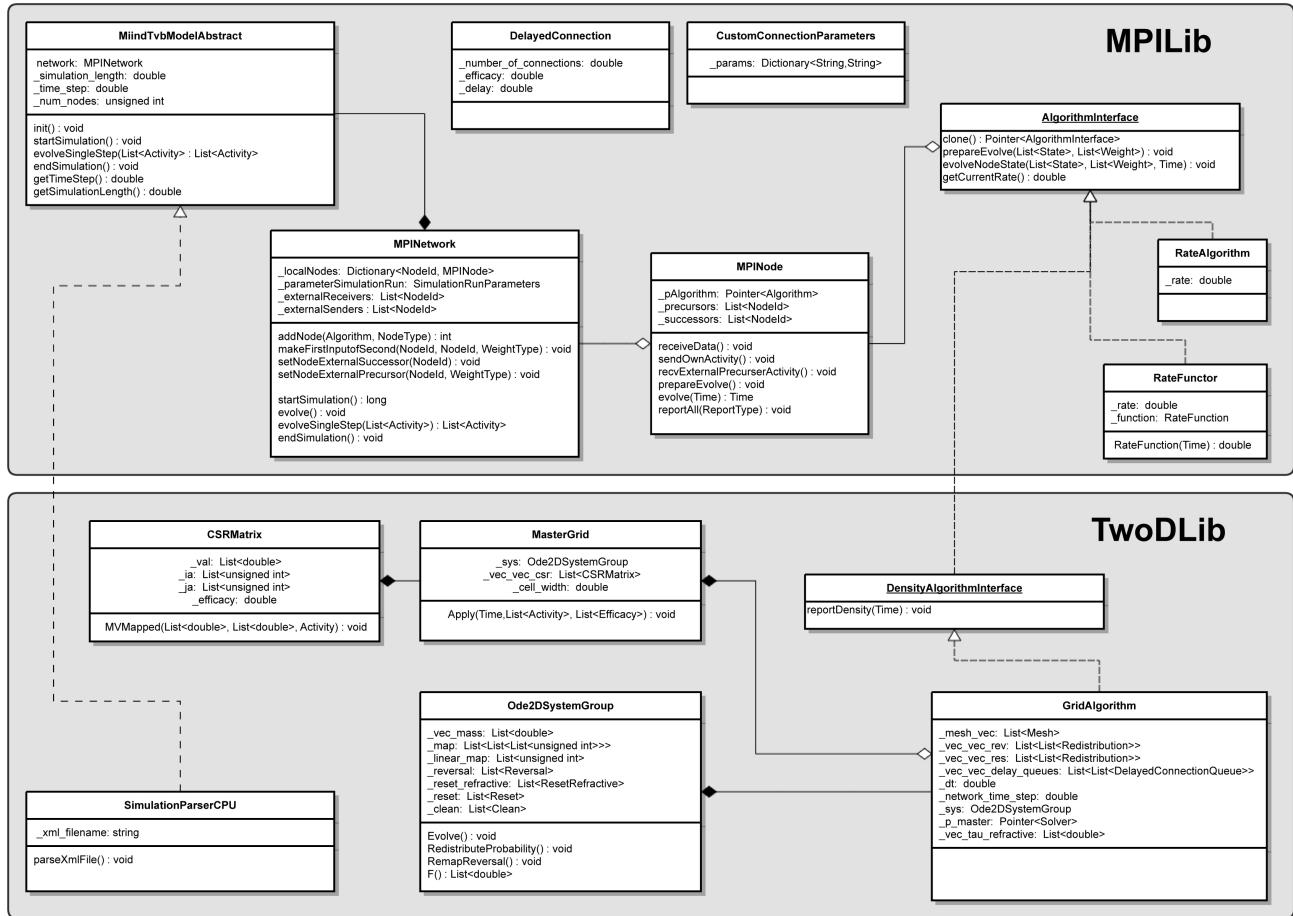
**Figure 9.** Heat plots for the probability density functions of two populations in MIIND. Brightness (more yellow) indicates a higher probability mass. (A) When the Poisson master equation is solved, probability mass is pushed to the right (higher membrane potential) in discrete steps. As time passes, the discrete steps are smoothed out due to the movement of mass according to the deterministic dynamics (following the strip). (B) A combination of mass travelling along strips and being spread across the state space by noisy input produces the behaviour of the population.



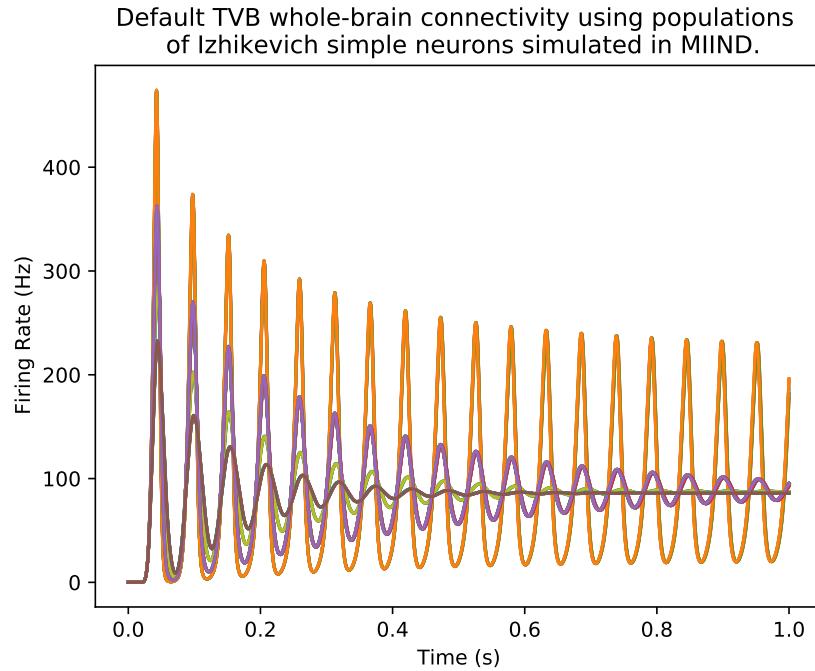
**Figure 10.** The MIIND processes and generated files required at each stage of pre-processing for the mesh algorithm. The shaded green rectangles represent automated processes run via the MIIND CLI.



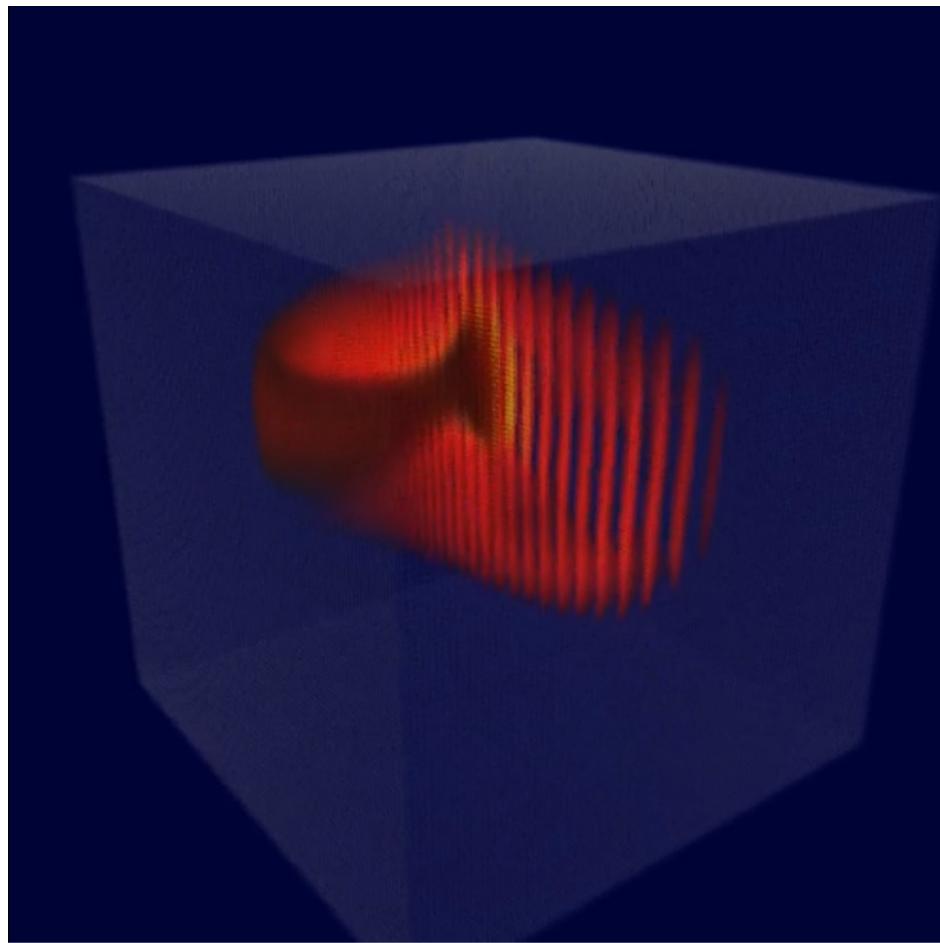
**Figure 11.** (A) The average firing rate of a population produced by calling the **rate** command. (B) A density plot of the population produced by calling the **plot-density** command. (C) The marginal density plots produced by calling the **plot-marginals** command.



**Figure 12.** A minimal UML diagram of MIIND. The two major libraries, **MPILib** and **TwoDLib**, are represented.



**Figure 13.** The firing rates of 76 nodes from the default TVB connectivity simulation. Each node is a population of Izhikevich simple neurons simulated using MIIND. The majority of nodes produce oscillations which decay to a constant average firing rate. However, a subset of nodes remain in an oscillating state.



**Figure 14.** (A) A density plot of a population of Hindmarsh-Rose neurons. The density is contained in a three dimensional volume such that each axis represents one of the time-dependent variables of the model. The volume has been rendered from a rotated and elevated position to more easily visualise the density.