Silicon Cellular Morphology

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1 Introduction

Neuromorphic engineering is both an exploratory activity within neurobiology and a methodology for system synthesis. In its role as a methodology for system synthesis, the emphasis is, rightly, placed upon emulating or replicating *function*. However, in its exploratory capacity, it may be necessary to emulate or replicate other neurobiological properties. The work reported here considers the morphological properties of excitable cells, and examines the possible effects of morphology upon function. To investigate morphological properties we show how to construct silicon "cells" with their own morphology. We describe a design technique that concentrates on emulating morphology by (i) exploiting the intrinsic properties of transistors and the materials from which they are composed and (ii) exploiting the physical equivalence between transistors operating in the weak-inversion region and excitable cell membranes. This physical equivalence is used more directly than the more frequently used design technique which attempts to match devices and circuits commonly used in traditional integrated circuit design, with mathematical variables used to describe neurobiological properties. At the very least, the design technique originating from electrical engineering requires more methodological stages than this technique emphasising cell morphology.

We suggest that it maybe illuminating to look at the evolution of excitable cell and nervous system morphology, in an attempt to address the issue of whether morphology determines function, or whether other mechanisms, such as ion channel distribution are crucial in determining function. In addition, this may encourage the application of neuromorphic engineering techniques to systems outwith the arthropod and chordate phyla.

2 Evolution of Excitable Cells and Nervous Systems

Wherever there is a difference between the concentration of ions between the inside and the outside of a cell, an electrical potential difference arises across the barrier between the two – the cell membrane. The actual potential difference depends on the relative concentrations of all the ions [8]. For cell structures of finite size, a change in potential at some point takes time to propogate to other points on the cell. This time delay is defined in terms of the length constant of a core conductor model, which in turn depends on the resistance of the core, and the capacitance of the membrane [8].

All the variants and features of signal propagation in cells and throughout nervous systems, such as graded and action potentials, are supported by ion channels. The evolution of excitable cells and nervous systems has developed a wide range of morphologies, from the fused nerve nets of coelenterates to the neural tube with fore–, mid– and hindbrain vesicles of vertebrates. However, ion channels themselves are molecularly at least, relatively conserved. What has altered are the species expressed, their densities and distributions. For example, Na^{++} channels are a relatively late evolutionary occurrence, as is the transition from generating graded potentials to

generating action potentials. Perhaps the simplest excitable cell / nervous system that can usefully be explored is that of a unicellular animal such as *Paramecium*. These animals function as a combined sensory receptor and effector, so the link between ion channels and observable behaviour is relatively direct. *Paramecium* are found free-swimming in freshwater pools. Upon encountering an obstacle mechano–sensitive Ca^{++} channels are opened. The resulting depolarising potential activates Ca^{++} channels in the ciliary membrane, turning the orientation of the ciliary power stroke, so that the *Paramecium* swims backwards, until K^{+} channels are activated, repolarising the cell.

Figure 1, shows an illustration of the anterior half of a cell. It could represent a unicellular animal, such as *Paramecium*, with ciliate processes, or it could represent a neuron, with dendritic processes. It could also represent a segment of dendrite, with dendritic spines. All are composed of an intracellular fluid, bounded by a continuous lipid-protein membrane. A population of voltage–dependent ion channels is located in the anterior region of the cell, which become active due to input from sensory apparatus (*Paramecium*) or synapses (dendrite) located in this region. The depolarisation of the membrane results in an influx of cations to the intracellular space. The effect of the membrane voltage alteration and current flow through the ion channels will depend upon the morphology of the cell and upon the properties of the membrane, including the density and distribution of the ion channel population. The relative contribution of these factors is unknown. The current arising from stimulation of the anterior region may spread passively due to the cable properties of the cell, thereby depolarising the entire cell. Alternatively, if the ion channel configuration is "just right" (and this is thought to be constrained by the membrane hyperpolarising long enough for the ion channels allowing influx to deinactivate) then the action potential generation mechanism succeeds. Depending on the type of cell, signal propagation can result in behaviours ranging from the activation of a motor apparatus within the cell itself (as in unicellular animals), to a transfer of signals to other cells in a network (as in the nervous systems of multicellular animals).

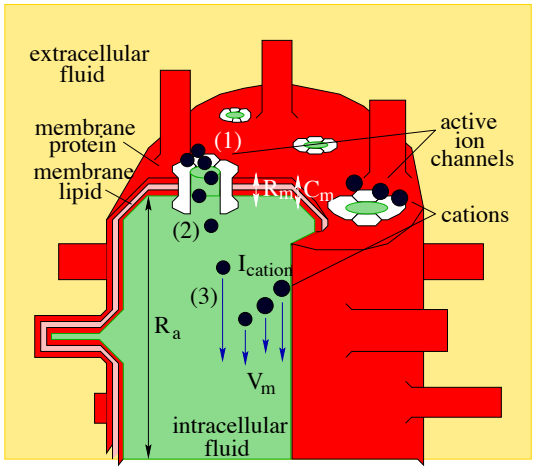

Figure 1: *The anterior half of a cell*

3 Methods: Designing with Algorithmic and Physical Equivalence

Carver Mead advocated the use of analogue VLSI as a technology for neurobiological modelling because he had a notion of a physical equivalence between excitable cells / nervous systems and FET-based silicon circuits [6]. Specifically, field-effect transistors operated in the weak–inversion

region (below the threshold for conduction of the main "population" of charge carriers), are subject to the same physical processes as ion channels in the cell membrane. The diffusion of charge carriers between extra– and intracellular regions, and between source and drain terminals, varies exponentially with a "barrier" voltage – cell membrane or gate terminal. Although the extent to which this is the case, and therefore of any significance, is disputed, this argument remains one of physics, rather than one of computationalism and all its associated problems [3]. However, a survey of "neuromorphic" work drawn from papers presented at the 1997 Neuromorphic Systems conference in Stirling shows that most work has moved away from designing using this physical equivalence (or resemblance). Instead designs use an algorithmic technique in which off–the–shelf devices are matched with mathematical models of the biological phenomenon under investigation. For example, in the case of the cell, there are mathematical models for the following three processes:

1. the membrane voltage-dependent process by which the population of ion channels become active (and inactive), and how this determines the current flow.
2. the change in membrane voltage produced by the current flow at the ion channel site.
3. the spread of current in the longitudinal direction of the cell.

The respective equations are:

$$I_{\text{cation}} = ((G_{\max_{\text{cation}}}.\text{inact}^a)\text{act}^b)(V_{\text{mem}}) \tag{1}$$

$$\frac{\delta V_{\text{site}}}{\delta t} = \frac{(I_{\text{cation}}.R_{\text{mem}}) - V_{\text{mem}}}{C_{\text{mem}}} \tag{2}$$

$$\delta V_{\text{mem}}(x) = \delta V_{\text{site}} e^{\frac{-x}{\lambda}} \tag{3}$$

I_{cation} is the current flow through the ion channel population, $G_{\max_{\text{cation}}}$ is the maximum conductance of the cation, $inact^a$ is an inactivation variable, act^b is an activation variable, V_{mem} is the membrane voltage, V_{site} is the membrane voltage at the ion channel site, t is time, R_{mem} is the membrane resistance, C_{mem} is the membrane capacitance, x is the distance in a longitudinal direction and λ is the membrane length constant.

The equivalent silicon circuit is designed as follows: the current through a transistor represents the current flow through a population of ion channels. The transistor current is dependent on the voltage gradient across the transistor which represents the membrane voltage and is modulated by the gate voltage. The gate voltage represents the process by which the population of ion channels become active and inactive. In terms of the polysilicon and active area layers of which a transistor is composed, this would have the layout configuration illustrated in figure 2.

A series of capacitors and resistors[1] represent the membrane. The change in membrane voltage is produced by the current flow at the ion channel site and the subsequent spread (and exponential attenuation) of current in the longitudinal direction of the cell. The layout configuration of this circuitry, added to the circuit depicted in figure 2, is illustrated in figure 3.

Differential pairs with a sigmoid transfer function and low-pass filter circuits are added to represent *act* and *inact*, the activation and inactivation variables. This results in a significant increase in both the number of devices and the area required. The final circuit resembles in part the silicon neuron circuitry of Mahowald and Douglas,[4] and the artificial dendritic tree of Elias [2]. Further capacitor and resistor compartments can be added to represent dendritic structures, where a representation of branching and of synaptic sites is possible.

The physical design technique is intended to exploit more fully the physical equivalence between transistors and membranes. The aim is to capture more of the properties of the membrane within the materials of MOS design themselves, rather than assigning membrane variables to representation by additional external and extrinsic circuitry. Whilst reducing the number of

[1]Resistors can be implemented with transistors or switched capacitors

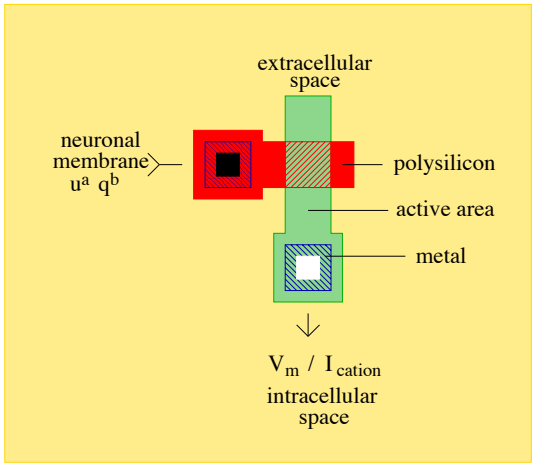

Figure 2: *The layout of the circuit representing the current flow through a population of ion channels.*

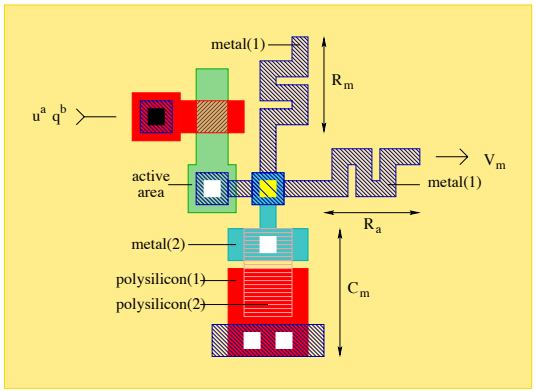

Figure 3: *The layout of the circuit representing the change in membrane voltage produced by the current flow at the ion channel site and the subsequent spread of current in the longitudinal direction of the cell.*

devices and area required, this also has the effect of allowing the morphological properties of membranes and cells to be emphasised. The significant morphological feature of the membrane is that it is continuous and divides extra– and intracellular spaces. This requires that the polysilicon gate of a transistor likewise divide external and internal spaces. The pores provided by ion channels in a biological membrane are provided by active area, creating source and drain regions either side of the polysilicon membrane. The layout for the cell could be as illustrated in figure 4.

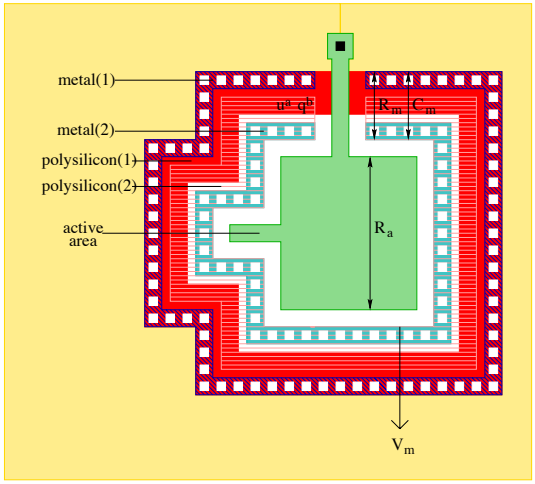

Figure 4: *The layout of the circuit designed for physical equivalence.*

4 A Comparison of the Two Design Techniques

We argue that for the biological operations of membrane voltage alteration and subsequent current flow, the physical design technique produces a more efficient model than the algorithmic design technique. Firstly, the additional external circuitry required to represent the activation and inactivation variables in their algorithmic form results in a greater number of devices, hence noise, and a greater area of silicon being used. Further, designing with algorithmic rather than physical equivalence offers less justification for choosing a neuromorphic engineering approach over a conventional simulation one. Given the time required for design and fabrication, implementing a biological system in neuromorphic hardware currently offers no advantages over simulation except where the system is required to operate in real-time or with real-world interaction, such as during locomotion.

However, there are wider issues, relating to the differences between *any* MOS–based system, whether designed with algorithmic or physical equivalence in mind, and biological phenomena. An example of this is the difference in *elements* available to both systems. The number of transistor types in conventional MOS–based systems is essentially two, n–type and p–type, using one charge carrier – the electron. Biological systems have hundreds of types of ion channels, with corresponding types of charge carriers, added to which these charge carriers can display cooperative properties [1]. Whilst it might be possible to increase the number of transistor "types" by varying substrate doping, this is not currently implementable using available manufacturing technologies. It is hoped that using a design technique that allows more complex morphologies than the rectangular–based conventional MOS designs and perhaps cross–sectional representations of cells, might go some way towards compensating for the lack of variability of elements in silicon. At the same time, as described previously, we are trying to explore the relationship between morphology, ion channel complement and function in biological systems. There is currently debate over the relative contributions to function made by these factors. Some studies have shown firing patterns

to be consistent over different geometries within a neuronal type [7], requiring only an alteration in ion channel distribution to produce an effect, whilst other studies have shown a spectrum of firing patterns can be produced by different geometries across neuronal types, with a common ion channel distribution. [5]. Also, morphological and ionic changes occur both pre– and post–natally in many animals, which gives us the possibility of exploring ontogeny in addition to phylogeny. We hope it will be possible to model the effect of the distance between ion channels, to model the ion channel configurations that are possible with a variety of geometries and to model the evolution of the generation of action potentials. In the exploration of the effects of form upon function, one of the questions that needs to be answered is whether the nervous system's structural diversity is seen as a compensation for deficits, such as relatively low speeds of transmission, or as an explanation for computation in the brain. More generally, neuromorphic engineering needs to decide whether it is more useful to continue to constrain the silicon technology in order to closely model the neurobiology, or to allow the properties of the silicon technology to determine the evolution of the silicon cells.

Acknowledgements

Catherine Breslin is funded by the Gatsby Foundation.

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