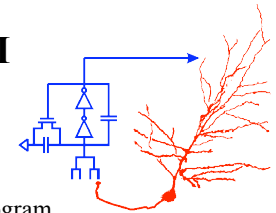




# Modeling the Head-Direction Cell System: a Neuromorphic VLSI Implementation

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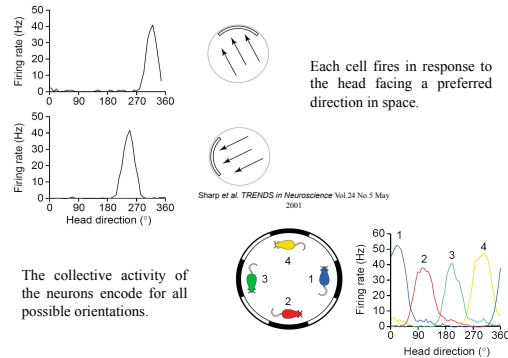
## Introduction

The Head Direction cell System (HDS) is a neural circuit of special interest for performing spatial navigation. The HDS is composed of neurons that preferentially fire when the head of the animal faces a particular direction in the environment. Using a population of neurons with different preferred directions, all directions can be represented. The HDS system represents the animal's current direction estimate by integrating rotational velocity information (from visual or vestibular sensors) or by receiving direct angular information provided by other sensory sources.

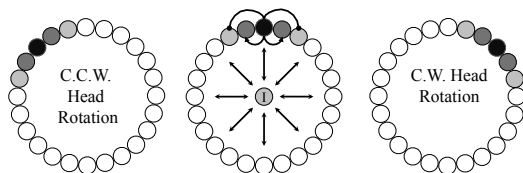
Many different models have been proposed to describe the computation performed in the HDS. In this poster, we present a neuromorphic VLSI chip implementation of an attractor model of the HDS. The chip was fabricated in a commercially-available 0.5  $\mu\text{m}$  CMOS process and is now being tested.

## Head-Direction Cell System Anatomy and Receptive Fields

"Head-Direction (HD) cells were first discovered in the postsubiculum of rats, however, subsequent studies have shown the existence of HD cells in many other areas of the rat brain. The specific functionality of these populations of HD cells differs with their location; as we are interested in the spatial navigation problem, we will focus on the HD cells in the postsubiculum.



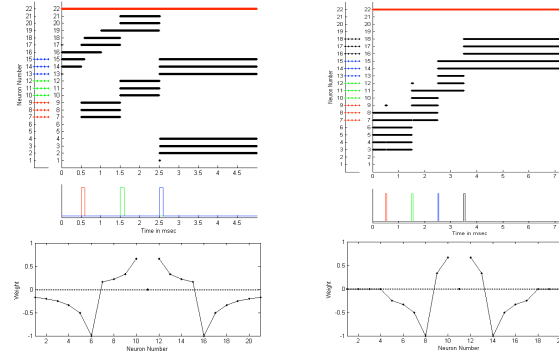
## System Model



The HDS is modeled as a ring of neurons acting as a recurrent network each neuron projects excitation to its nearest neighbors and inhibition to distant neighbors. There is a global inhibitory neuron that receives excitatory connections from all neurons and projects inhibition back to the ring globally. The global inhibitory connection acts as a "winner-take-all" which suppresses activity in weakly activated neurons.

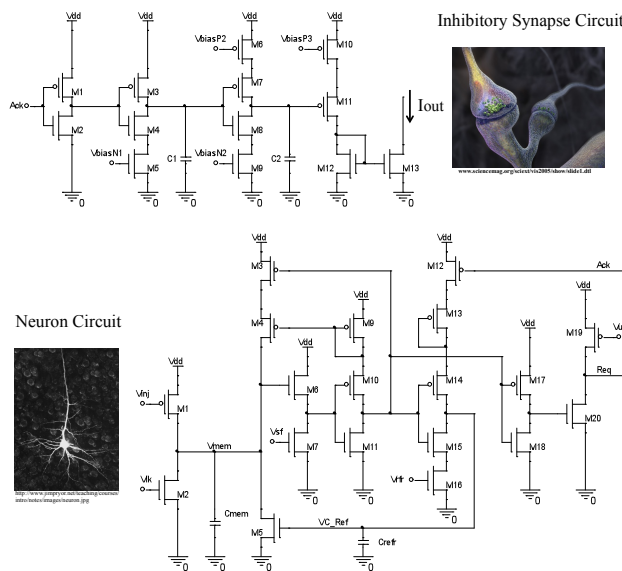
The activity pattern of the neurons encodes for the head direction space, and follows the head orientation as it rotates clock-wise or counter clock-wise.

## System and Circuit Simulations

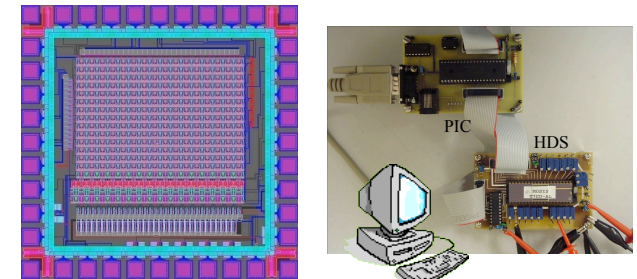


We have simulated an array of interconnected neurons with noisy versions of shown weight patterns to mimic the effect of mismatch in transistor fabrication. All neurons receive a small DC injection current. Due to inherent mismatch, the activity tends to center around a group of neurons creating a bump of active neurons which code for the initial head direction in the space. As the head turns, a directed input is injected into neurons coding for corresponding directions; this directional input comes from angular motion sensors, presumably from the visual and/or vestibular system. The result of this input is to move the bump of activity around the ring to follow the head, coding for the new head direction. Shown in red is the activity of the global inhibitory neuron, neuron 22. Notice that when the input is removed, neurons maintain their activity and the bump remains at its new location. The network provides a memory of direction by maintaining its activity in the absence of external input.

## Circuit Diagrams

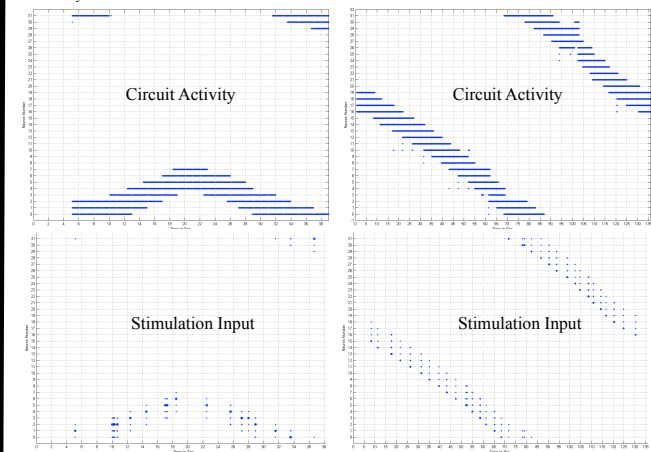


## Chip Design and Testing Results



We have designed an analog/digital neural circuit in VLSI to implement the HDS model presented. The chip consists of an array of 32 neurons each having 14 synapses (8 excitatory, and 6 inhibitory), allowing each neuron to connect to 14 neighbors (7 on each side). The weights of these synapses are set using DC biasing on the chip. The global inhibitory neuron receives excitation from all 32 neurons and projects inhibition back to all of them. The global inhibitory connections are hardwired on the chip with the ability to turn it ON or OFF using DC biasing. The Address Event Representation (AER) protocol is used to read the activity of the neurons and to implement the routing back to the chip through a PIC microcontroller (Microchip Inc).

Shown in figure is the circuit activity (top panels) and the corresponding input stimulation patterns (bottom panels). The input to the chip is in the form of AER spikes being sent to the required neurons using the PIC that implements the routing of the recurrent connections with the input stimulation spikes interleaved. When the circuit is first turned ON there is no sustained activity in the neurons, however, stimulation to a group of neurons results in a bump of activity being formed from the collective activity of these neurons. To move the bump, neurons at the edge of the current location are stimulated and the bump can be seen to move smoothly. It is important to note that the bump will remain stationary after the stimulation is removed.



## References

Sharp PE, Blair HT, Cho J (2001) The anatomical and computational basis of the Head Direction cell signal in the rat. Trends in Neuroscience, 24, 289-294. doi:10.1016/S0166-2236(00)01797-5

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