Path Planning Using Spike Propagation

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THIRTY YEARS OF SYSTEMS RESEARCH EXCELLENCE

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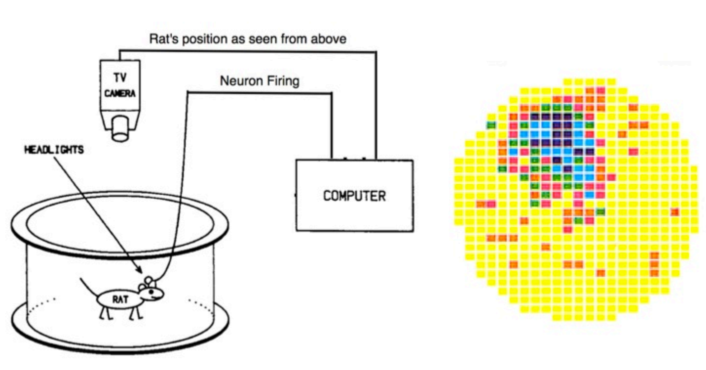
INTRODUCTION

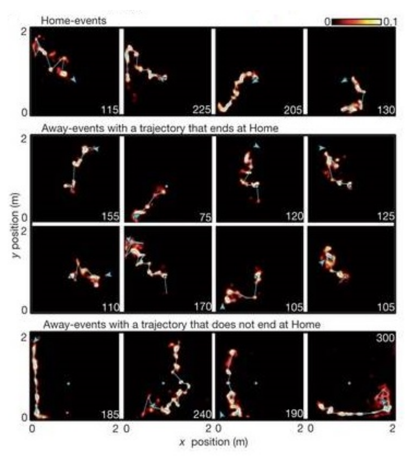
The development of mixed-mode VLSI circuits to mimic the computation of neural circuits ("**neuromorphic VLSI**") has a long history within ISR. Originally, the focus was purely on the **brainstem sensory circuits of echolocating bats**, but has since expanded to focus on questions of neural representations of **space and memory-assisted decision making**. Long-time collaborators include: P. S. Krishnaprasad, Cynthia Moss, Shihab Shamma, and Pamela Abshire.

The **hippocampus** is a mammalian brain area associated with the storage and retrieval of declarative memory (rodents, humans). Studied extensively in rats on spatial navigation tasks, hippocampal **"place" cells** activate at specific locations in a given environment, providing a glimpse into how mammals represent space in **world-centered (allocentric) coordinates**. In this work, we explore how place cells could be linked to form a map and how this "active" map could be used for path planning.

BACKGROUND



From: http://blog.brainfacts.org/2013/10/place-cells-remapping-and-memory/#.VRXgd_nF98E

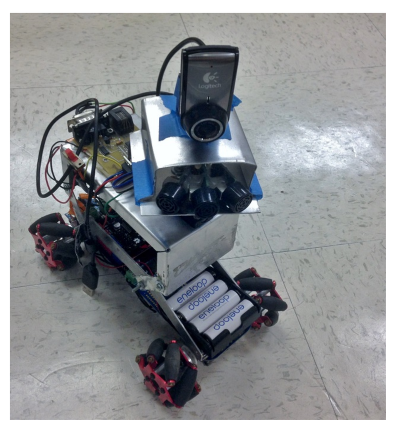


From: Pfeiffer, Brad E., and David J. Foster. "Hippocampal place-cell sequences depict future paths to remembered goals." *Nature* 497.7447 (2013): 74-79.

As depicted in the figure above (left) from O'Keefe and Nadel (1978), the recorded neuron fires **spikes** when the rat is in a **particular region** on the far end of the arena, **independent of the orientation** of the animal. These regions of activity vary from neuron to neuron in both size and shape.

Whenever the rat's motion is interrupted by pauses (or during slow-wave sleep), an intermittent bursting activity is observed, which is characterized by high frequency oscillations in the local field potential (100-150Hz) called "**sharp waves**". Sharp wave events correspond to place cell activation sequences, that sometimes represent paths just taken in forward or reverse order. A recent study by Pfeiffer and Foster (2013; above right), reported goal-directed planning activity in the hippocampus of an awake rat during these sharp wave events. They found a high coherence between the sequences extracted from the sharp wave events and the **paths taken by the rodent in the future** and a lower coherence for the paths taken in the past.

Path planning has been exhaustively studied by the artificial intelligence and robotics communities. Our aim, however, is to use **neurobiologically plausible** network architectures to explain how the place cell representation can be used to implement path planning. In particular, we are interested in how variations in map acquisition and representation can lead to different paths and different mechanisms for implementation. We demonstrate some of these models here in a neuromorphic-VLSI circuit implementation.



MODEL

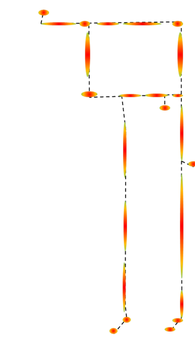
In our working model, we assume that place cell activity is the result of the coordinated **integration of both odometry and the sensory recognition** of place. We do not assume that all physical locations on the map are represented by place cells nor do we assume that all place fields are circular.

Through exploration, we assume **that place cells become linked** (bidirectionally) to each other synaptically when it is **possible to travel** between places.

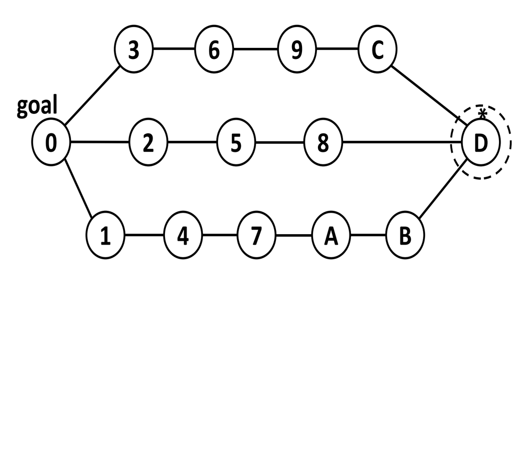
A **topological map** is thus embedded in the network in the form of a graph where the nodes are places and the links represent knowledge of traversibility between places.

Consider the example of a creature exploring the 2nd level of the A. V. Williams building (left figure). By allowing place fields to represent regions that are equivalent from the point of view of the present task (e.g., finding the Horiuchi laboratory), **place fields could be long and narrow in the hallways and circular at hallway intersections.** These place cells would then be **synaptically linked** along with information about their relative orientation (right figure).

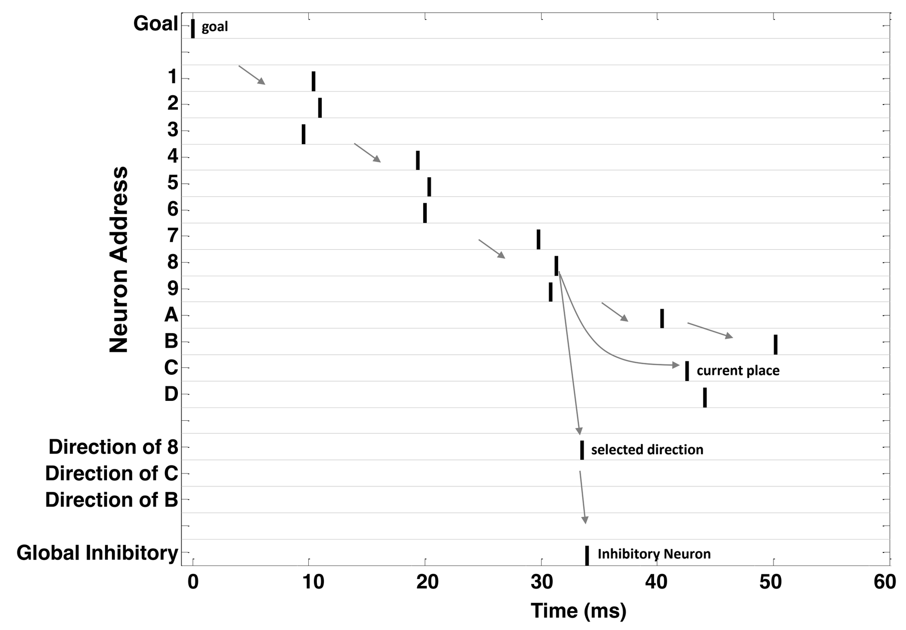
Floor plan of AV Williams Level #2



Example: The spatial representation of linked place cells based on limited exploration in a given environment. (conceptual)

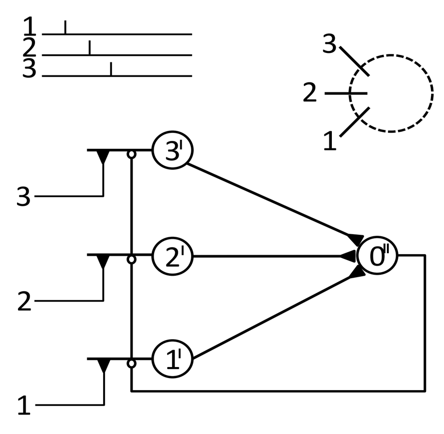


Concept graph showing 3 paths

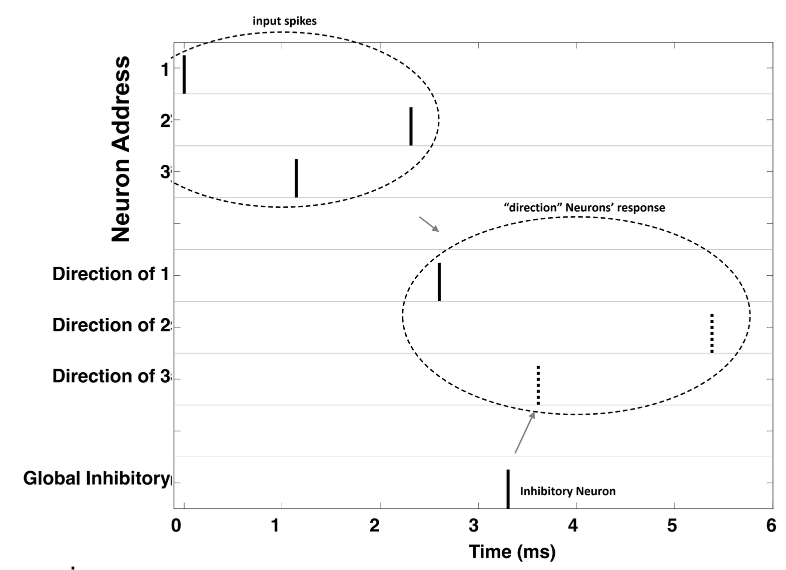


Spiking activity captured from the chip

We use a **spiking neural network** to implement this graph. If we stimulate a node (i.e., cell) in the graph that represents a desired destination, bidirectional synaptic links **spread the activity** in all directions on the graph eventually arriving at the cell representing the animal's current location. By monitoring the direction (at the current location's place cell) of the first arriving spike using a **temporal winner-take-all network**, the next place field on the "shortest" path (i.e., the next waypoint) is revealed.



A Temporal Winner-Take-All Network: Inputs1,2,3 represent spikes coming from neurons representing places. Nodes 1',2',3' receive inputs from 1,2,3 neurons and these are called direction neurons. 0" is an inhibitory neuron and selects the first activated direction neuron

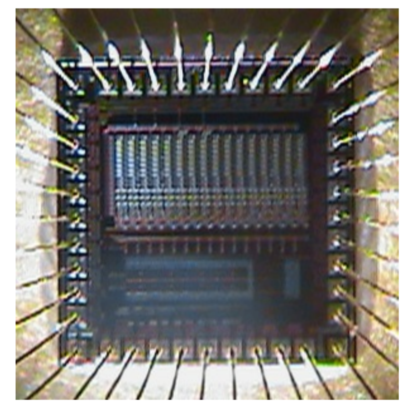


The spiking activity of the direction neuron is captured here

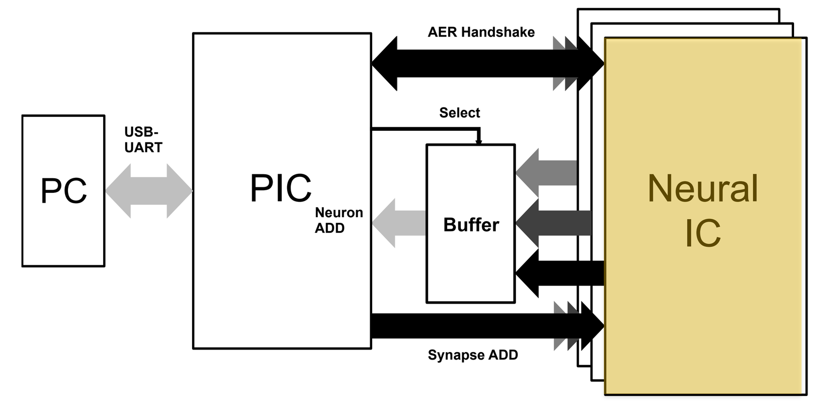
Similar models such as the one proposed by Filip Ponulak (**2013**) alter the synaptic weights of the network during the planning process to store the desired path. Although desirable for many reasons, storing and accessing the full plan is not necessary to execute the path. In our simulations, the **planning process is repeated after each waypoint is reached** to provide instructions for the next action until the goal is reached. This architecture can choose the **shortest path** even with **multiple choices of destinations**. Current information about the environment (e.g., knowing the location of a hazard or blockage) can be injected into the path planning process by changing the propagation speed of spikes (through synaptic or neuronal modulation).

HARDWARE

The hardware setup consists of 3 neuron chips and a microcontroller that maintains a lookup table for the network connectivity. The Address-Event Representation is used for communicating the occurrence of neural spikes between devices. The microcontroller is also connected to a PC for data capture and control.

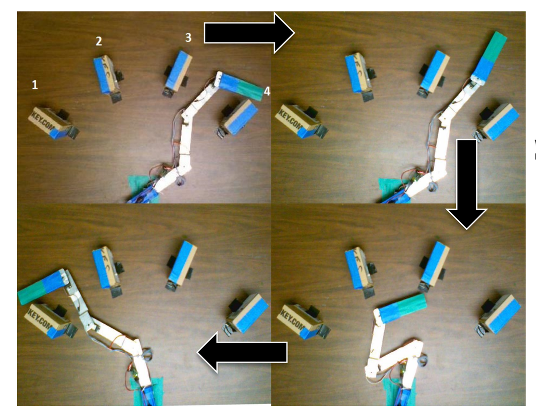


The Neural IC, 0.5 um CMOS process fabricated by MOSIS

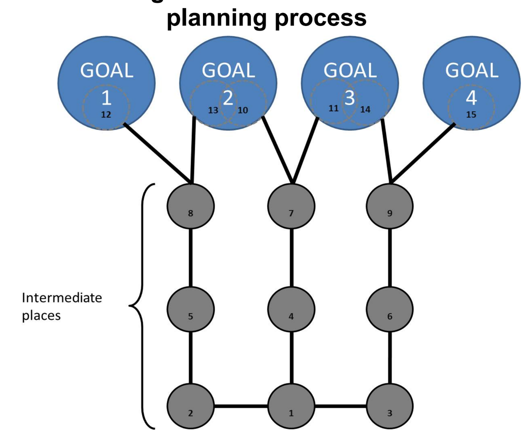


System setup

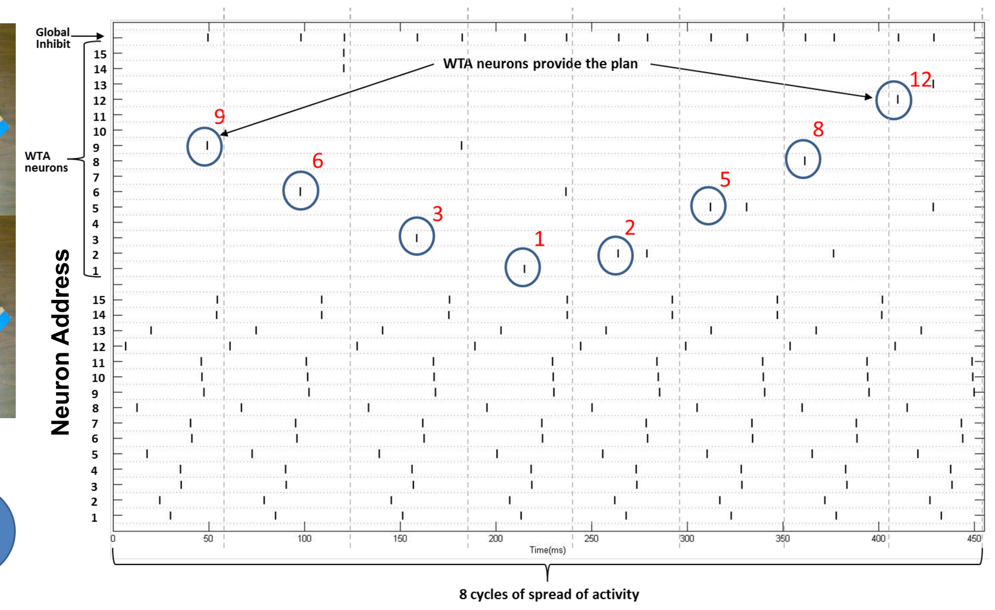
Application Example: Planning in robot arm joint-space. The 15-state network depicted below (left) is used to control a robotic arm. Each node represents a configuration in space. The spread of activation from the goal-node to current location-node in the network is used to identify the next arm movement. After completing the movement, the spread of activation is repeated, incrementally moving the arm along the shortest path through the joint-space graph. The activity of the neurons in the VLSI hardware is shown below (right panel) for a full sequence of movements from state 15 to state 12. Goals 2 and 3 are multiple-node goals (either node is acceptable) and the path-planning mechanism activates both nodes.



A four segment arm is used to test the planning process



A graph that depicts the configuration nodes 1-15 and goal states 1-4



Planning process from current state 15 to goal state 12. The spikes start from the goal state 12 and this process is repeated until the goal state is reached.

FUTURE WORK

- In this work, we assumed the existence of an accurate map (i.e., graph of states) and that the appropriate action to move from state to state was known. In our future work, we will develop exploration algorithms that can create this map of states and actions.
- We will continue to explore the connections between the observed biological sharp-wave phenomena in the hippocampus and our model of path planning.
- The hippocampus is also implicated in *episodic memory* in humans, a form of high-level memory that links many different contextual and sensory inputs. A mechanism that can explore these memories may provide a substrate for problem-solving through the recall of similar situations.

REFERENCES

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