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Velocity-Tuned Oscillators for NeuroSLAM and Spatial Navigations

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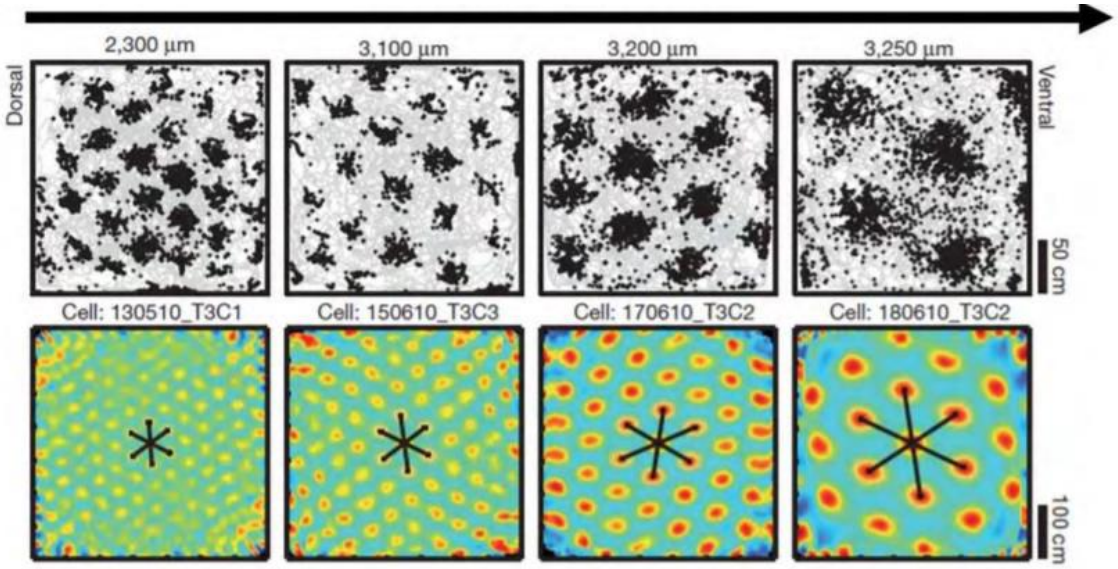
CAS

Motivation: 2014 Nobel Prize – A Neural Positioning System

- 2014 Nobel Prize in Physiology and Medicine awarded to John O'Keefe, May-Britt Moser, and Edvard Moser
  - Place cells (O'Keefe) form a map of an environment, while grid cells (Moser) form a coordinate system of the environment



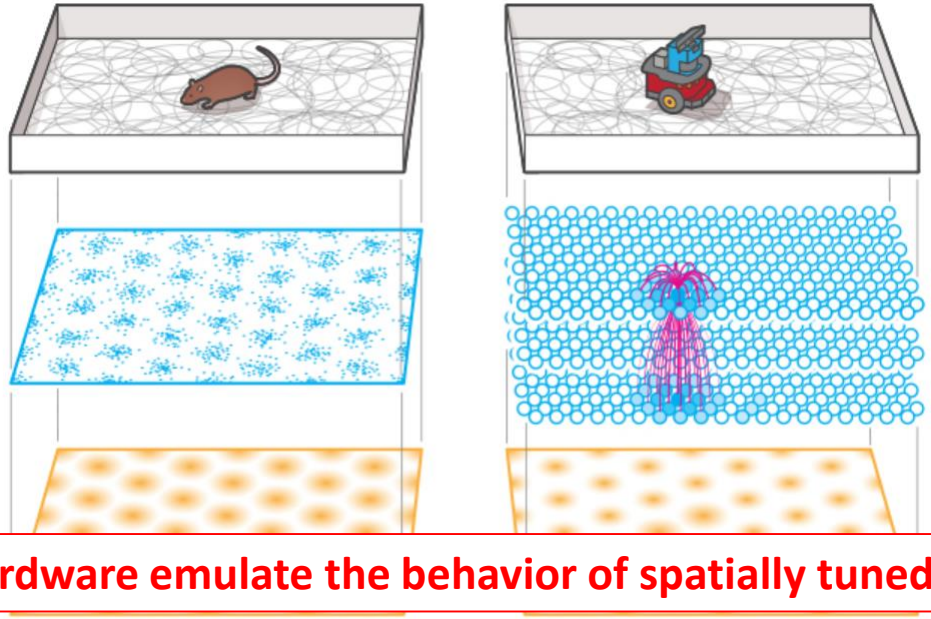
2014 Nobel Prize for Physiology or Medicine: Edvard Moser, May-Britt Moser and John O'Keefe

Brain is an excellent navigation system and can efficiently map an environment

H. Stensola, T. Stensola, T. Solstad, K. Froland, M. Moser, and E. Moser, "The entorhinal grid map is discretized," Nature, vol. 492, pp. 72-78, 2012

Motivation: 2014 Nobel Prize – A Neural Positioning System

- Central challenge in robotics: Simultaneous Localization and Mapping (SLAM)
  - Grid cells perform path integration to track animal location
  - Place and border cells represent environmental features into a cognitive map
  - Sensory fusion of odometry, proprioception, vision, *etc.* serve as input to navigational system



Can neuromorphic hardware emulate the behavior of spatially tuned cells in the brain?

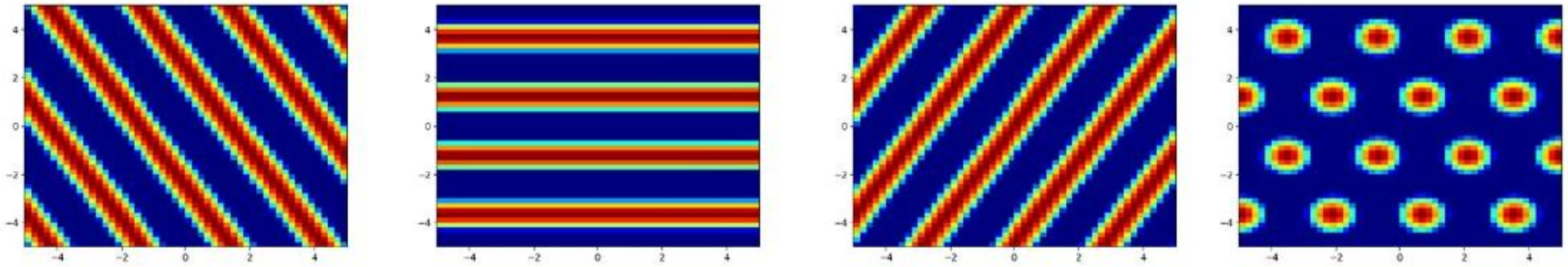
Illustration: James Provost

Kumagai, Jean. "Special report: Can we copy the brain?-Navigate like a rat." *IEEE Spectrum* 54.6 (2017): 58-63.

Models of Spatial Representation

- Continuous Attractor Networks (CAN)
  - Network activity converges towards stable patterns which is shifted by sensory input

- Oscillatory Interference (OI)
  - Phase interference between Velocity Controlled Oscillators (VCOs) causes stable spatial patterns
  - Bank of VCOs with preferred direction and speeds
  - Pseudo-Fourier decomposition of spatial responses into sums of sinusoids



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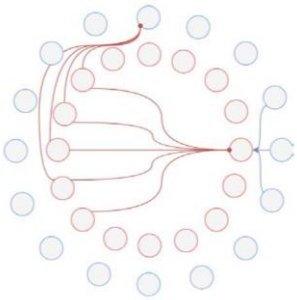
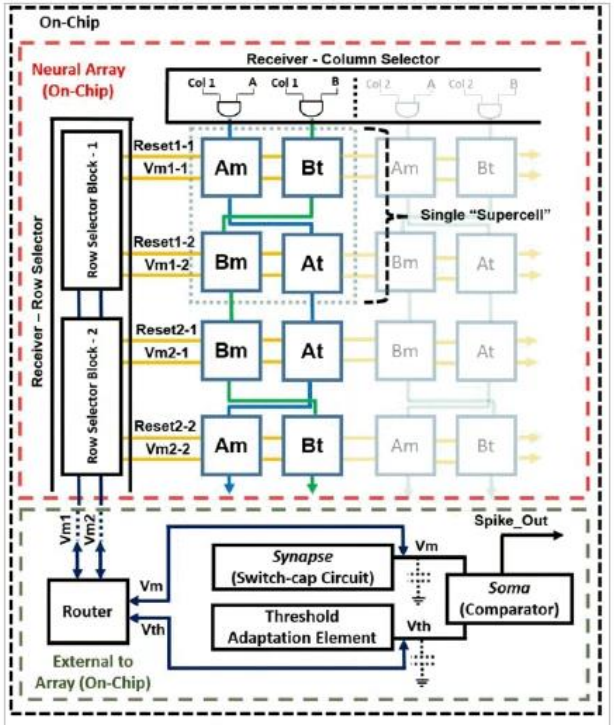
Welday, Adam C., et al. "Cosine directional tuning of theta cell burst frequencies: evidence for spatial coding by oscillatory interference." *Journal of Neuroscience* 31.45 (2011): 16157-16176.

VCO on Spiking Neuromorphic Hardware, ISCAS 2019



- Implemented spiking Velocity Controlled Oscillator (VCO) on Integrate and Fire Array Transceiver (IFAT)
- IFAT implements array of analog Mihalas-Niebur neurons
  - Via switch-capacitor circuits
  - Single switch-capacitor synapse
    - For all connectivity between neurons
    - 5-bit synaptic weight
  - Spike events processed using Address Event Representation (AER)



Cellon, Adam B., et al. "Velocity-Controlled Oscillators for Hippocampal Navigation on Spiking Neuromorphic Hardware." *2019 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2019.

Molin, Jamal Lottier, et al. "Low-power, low-mismatch, highly-dense array of VLSI Mihalas-Niebur neurons." *2017 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2017.

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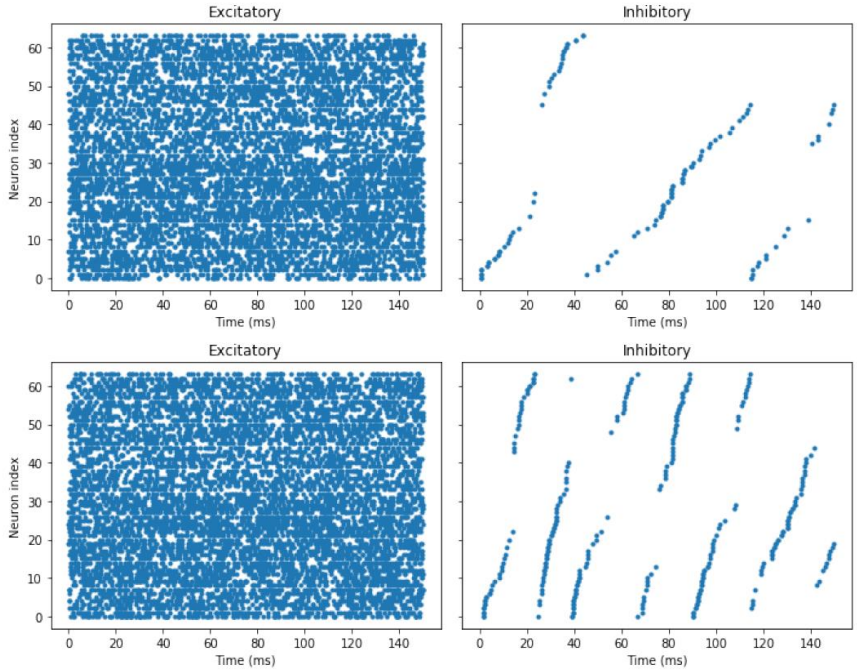


- VCO model too feedback-heavy for IFAT architecture
  - Single VCO consumes 128 of 4096 neurons
  - Synaptic resources scale poorly

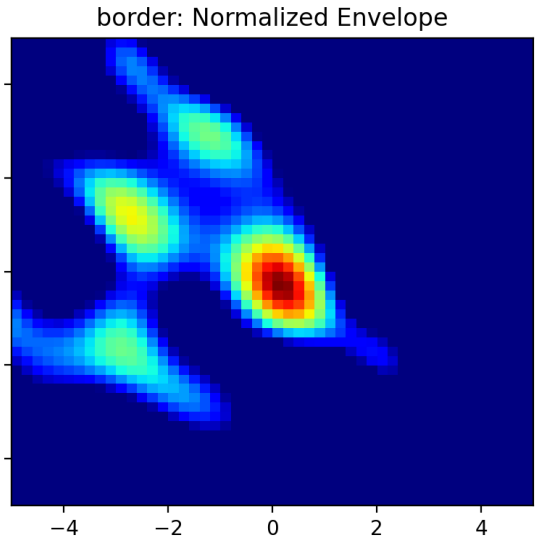
Development of custom VCO ASIC to provide velocity tuned theta oscillations as input to IFAT

Cellon, Adam B., et al. "Velocity-Controlled Oscillators for Hippocampal Navigation on Spiking Neuromorphic Hardware." *2019 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2019.

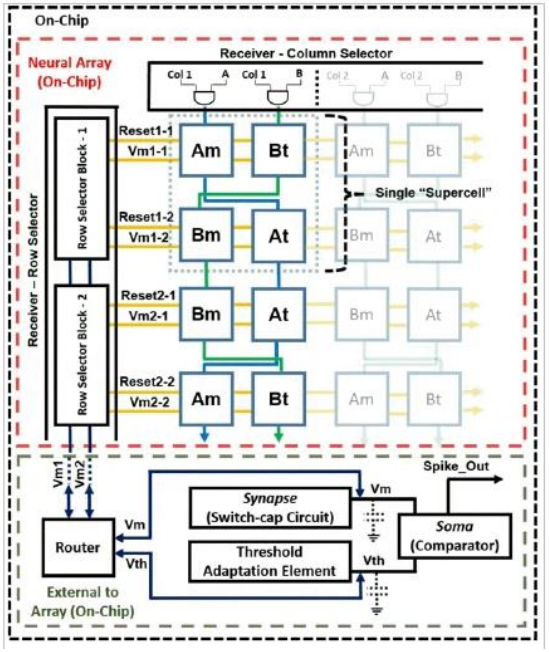
Realization in Neuromorphic Hardware

An array of 128 velocity tuned oscillators (VCO) characterized by:

- Oscillation frequency
- Oscillation phase
- Preferred velocity vector



An Integrate and Fire Array Transceiver (IFAT) interferes oscillations to realize spatially tuned cells



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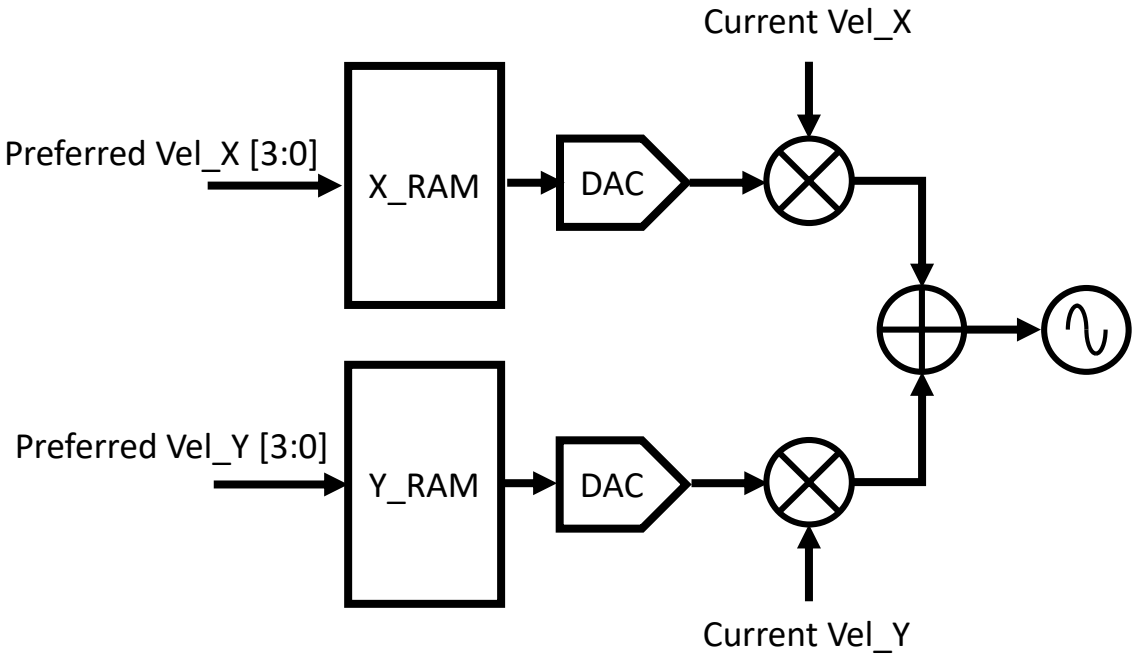
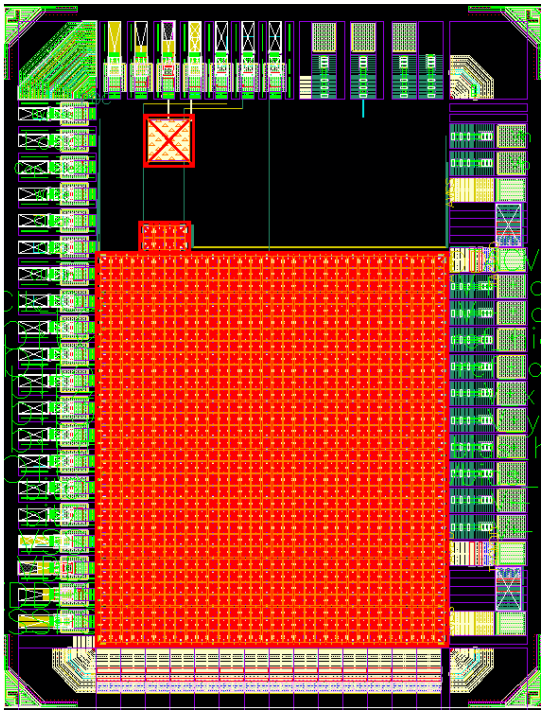
Velocity Controlled Oscillator Chip

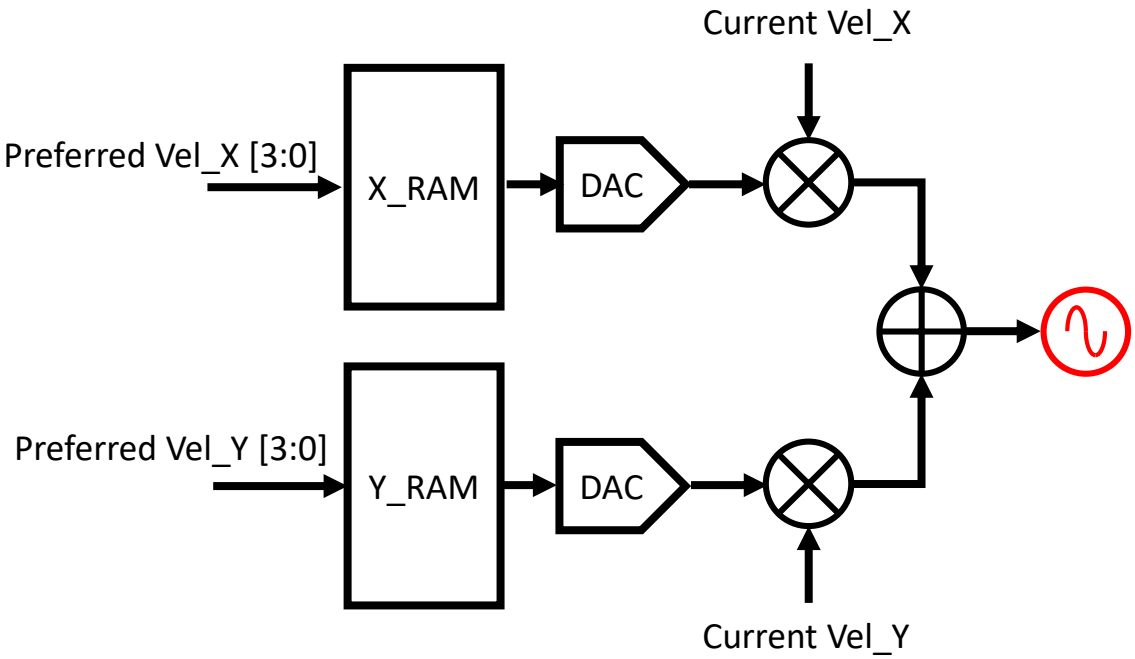
- Two SRAM units store preferred velocity in the X and Y direction
- Gilbert cell multiplier generates the drive current for the ring oscillator
  - Multiplier signal is proportional to the dot product of the current velocity and the preferred velocity

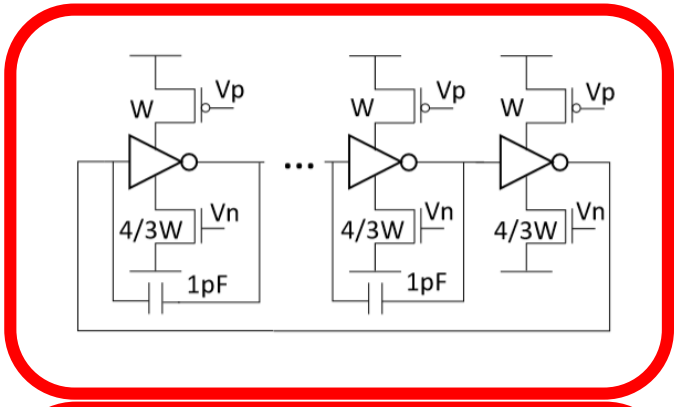


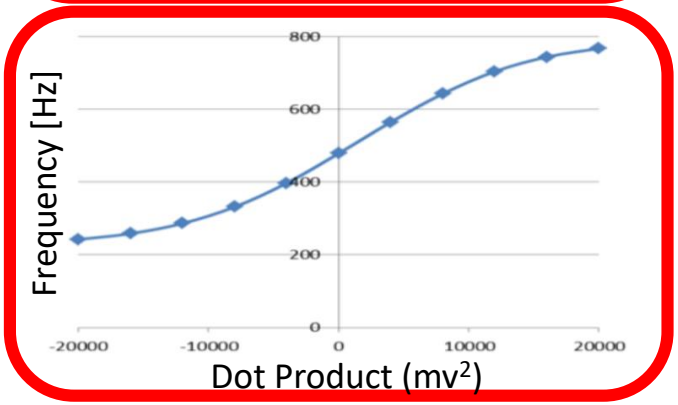


Oscillator Architecture

- Current starved ring oscillator is the key component of our design
  - Control current for the oscillator is provided by the dot product circuit

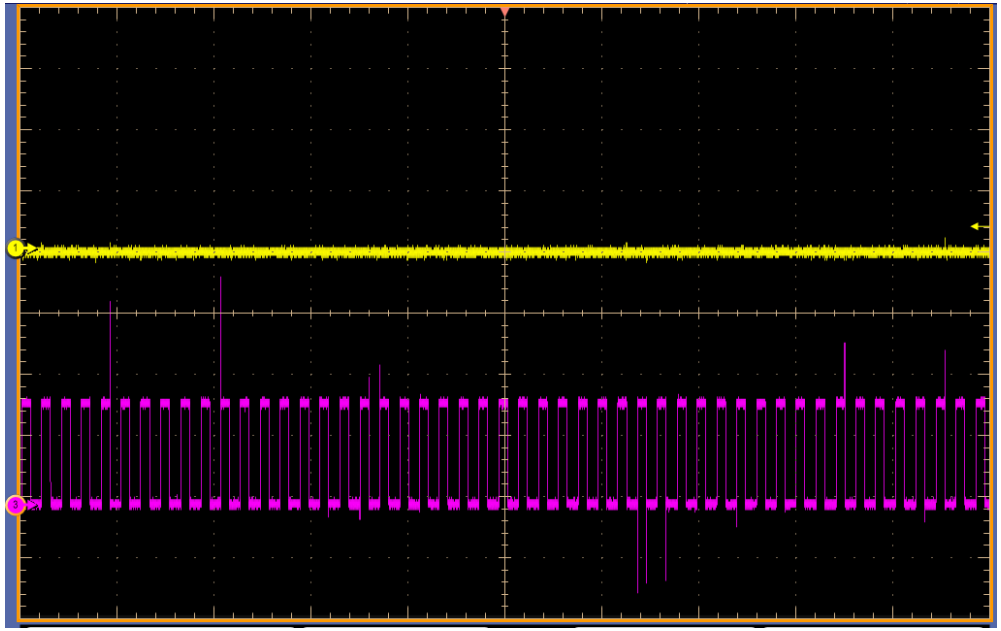


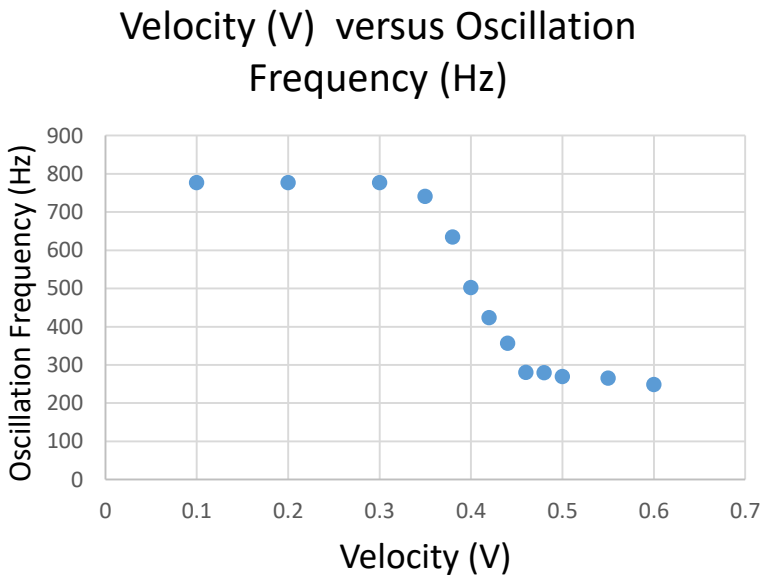




Velocity Controlled Oscillator – Preliminary Results

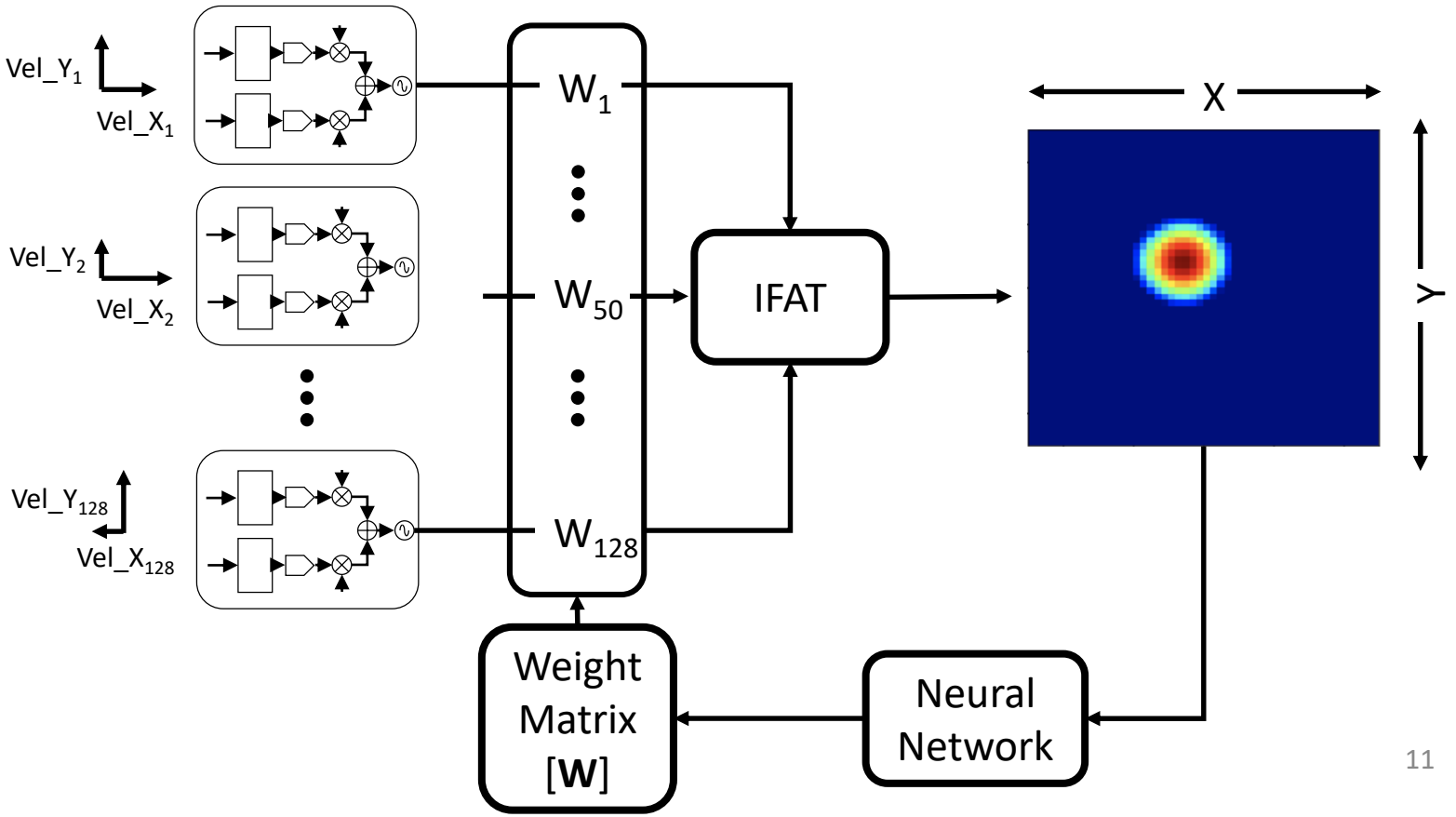
- An array of 128 Oscillators are fabricated in 65nm process
  - Each VCO is programmed at power up with it's preferred velocity vector in the cartesian coordinate
  - Output from all the 128 VCOs are multiplexed into a single output which is fed to IFAT for serial addressing and interference





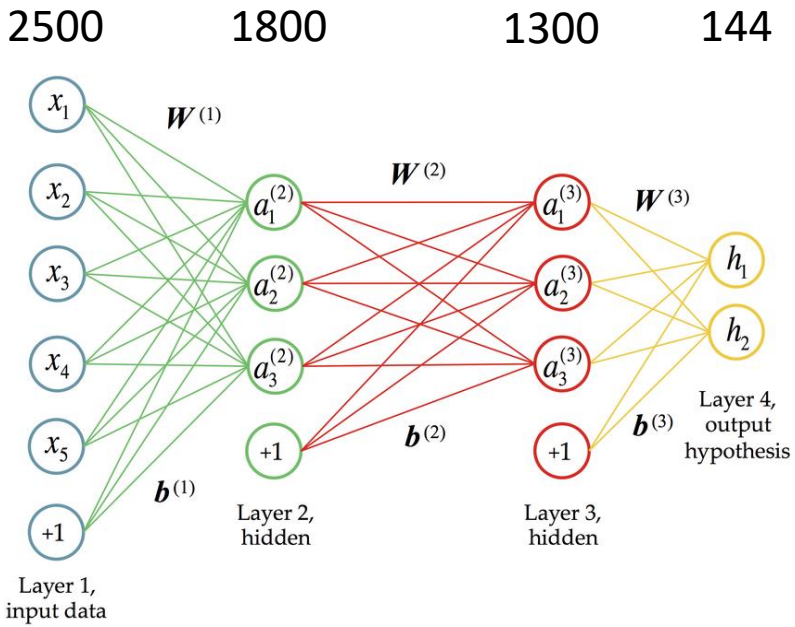
Using the VCO chipset for navigation and mapping

- Firing is characterized by interference between multiple VCO units inside the IFAT
  - Weight matrix (**W**) defines unique spatially tuned cells
  - Goal is to reverse engineer these weights given a known spatial cell



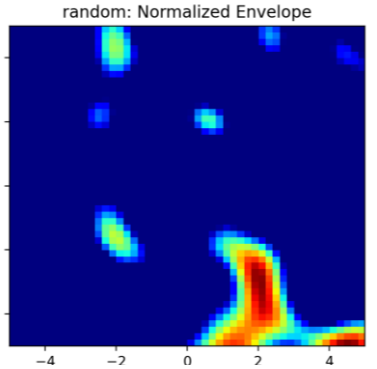
Neural Network – Training on the forward OI model

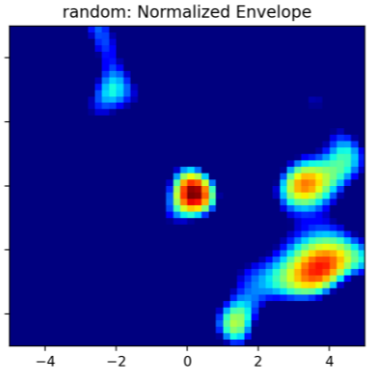
- Network is trained using back-propagation technique
- Train/Test ratio was set to 80/20
- Two features of 72 VCOs



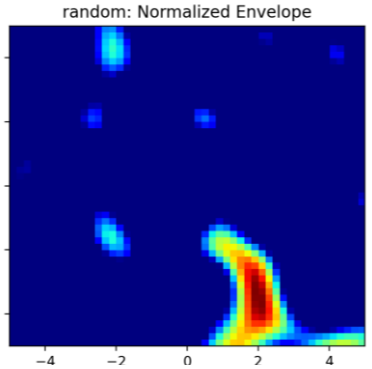
Results (normalized)

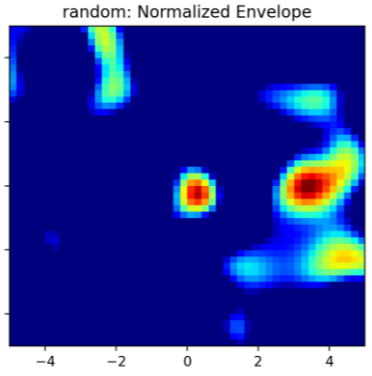
Expected





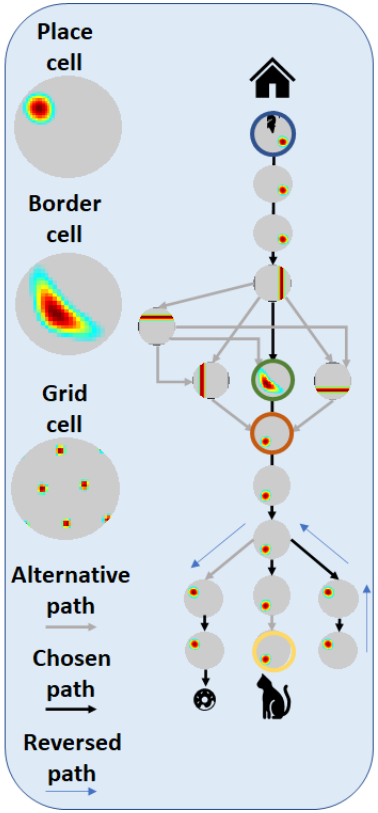
Obtained (from NN)

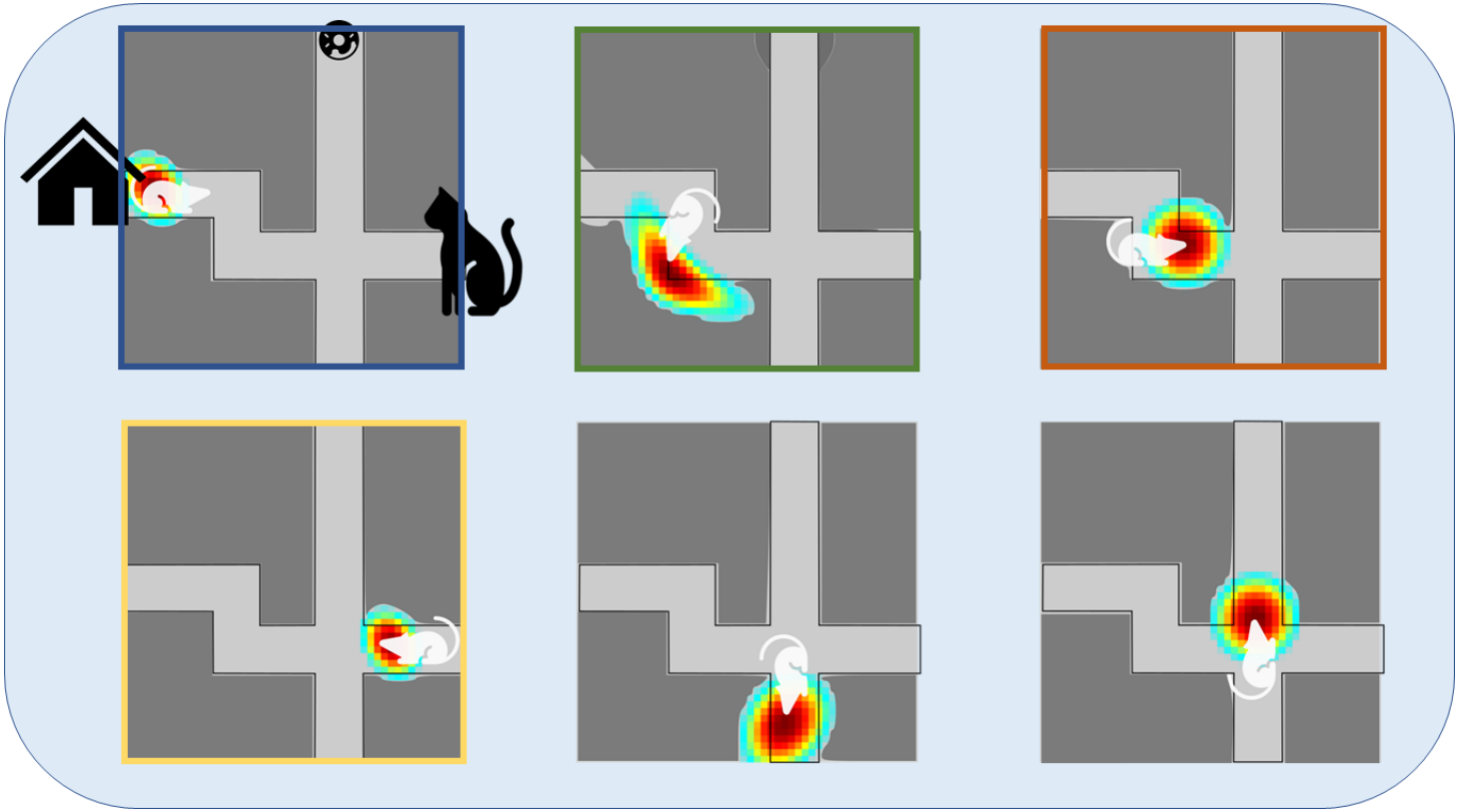




Next Step: Robotic Navigation

- Weights associated with spatial cells obtained through neural network algorithms are used to construct a map
  - Interference patterns for different weight matrices helps robot navigate its environment





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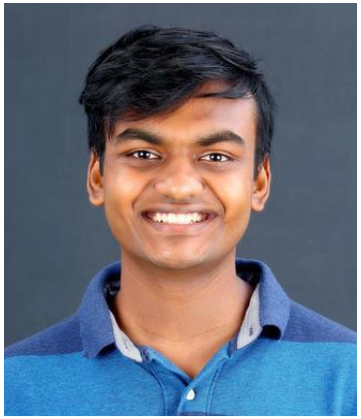


We would like to thank Toshiba Corporation for their support in this work