The Navigation Mechanism in a Rat's Brain

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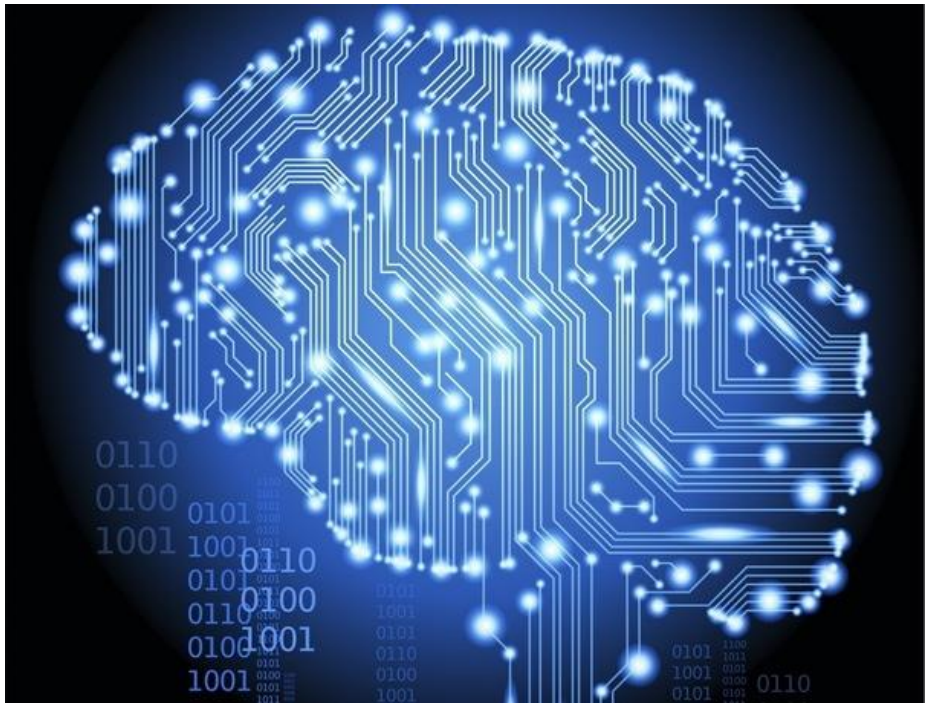
The purpose of this study

- Learn from nature
- Gain insights into nature

➔ Transfer findings into AI techniques



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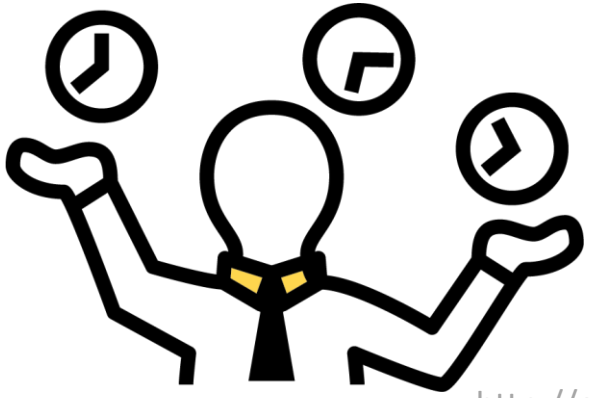
Learn from nature

- Building-Block Mechanism
- Lateralization
- Time Representation

http://think-bomb.blogspot.com



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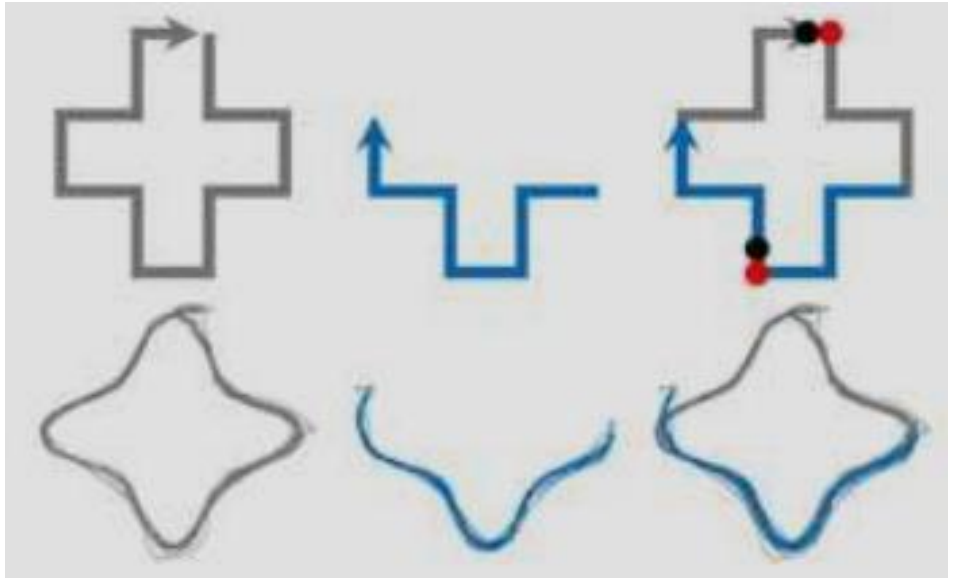

Image Source: A. S. Alexander, D. A. Nitz, *Current Biology*, 2017

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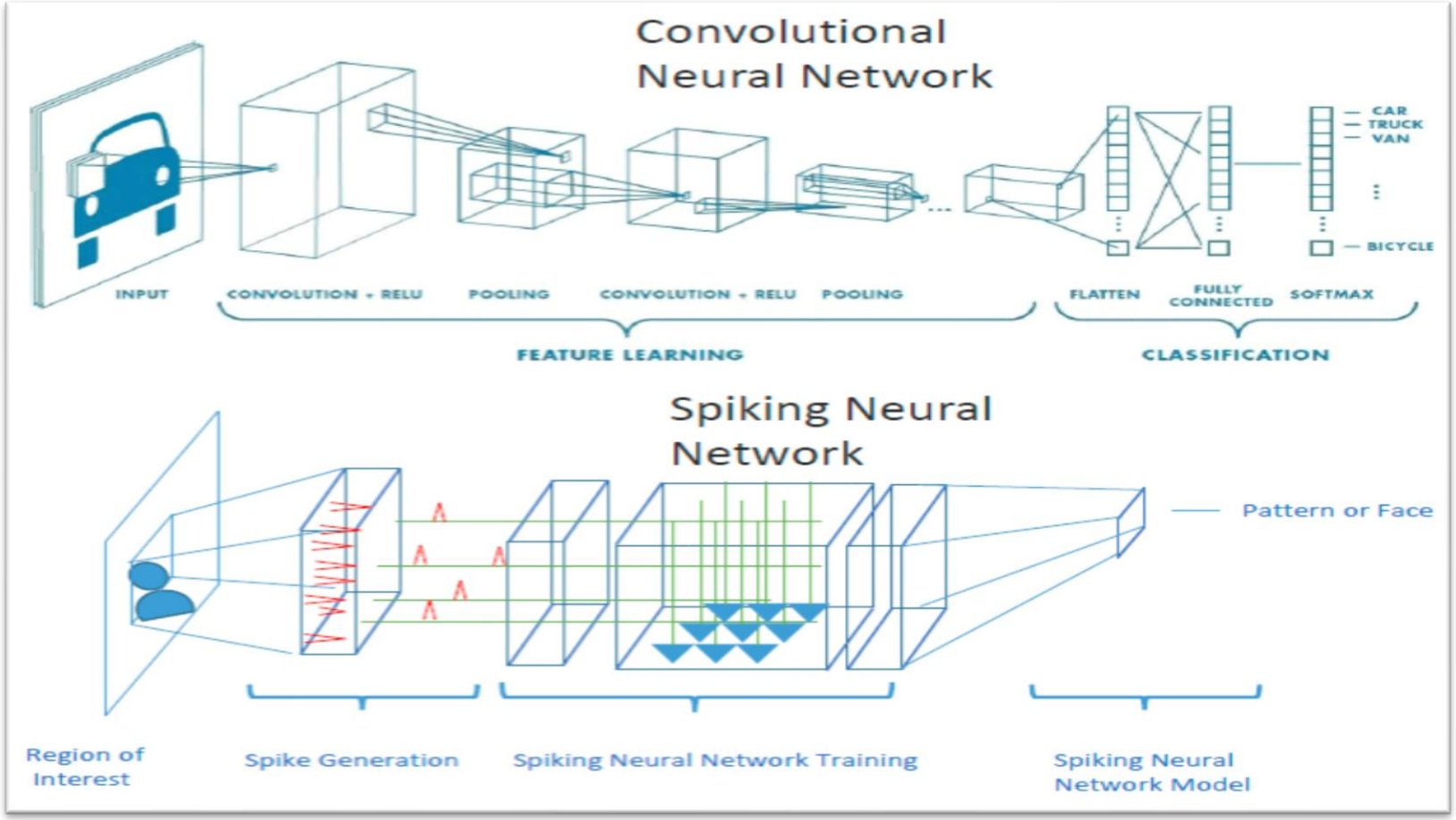
Generate insights into nature

- Using **Spiking Neural Network** to build biological non-implausible models to test hypothesis about the brain



Spike Timing Dependent Plasticity

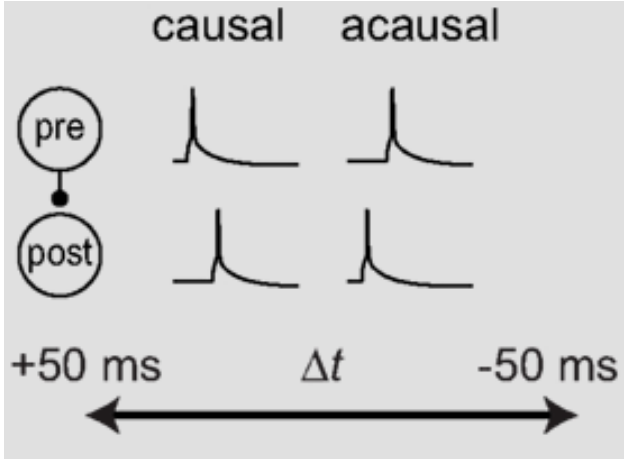


Image Source: W. Wong, *Electronic Design*, 2017; H. Markram, *Front. Synaptic Neurosci.*, 2011

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Why chose “Navigation”?

- A fundamental aspect of our intelligence:
  - self-localize in the environment (landmark utilization)
  - update one’s position on the basis of self-motion (path integration)
- Easy to test and compare with existing data and models

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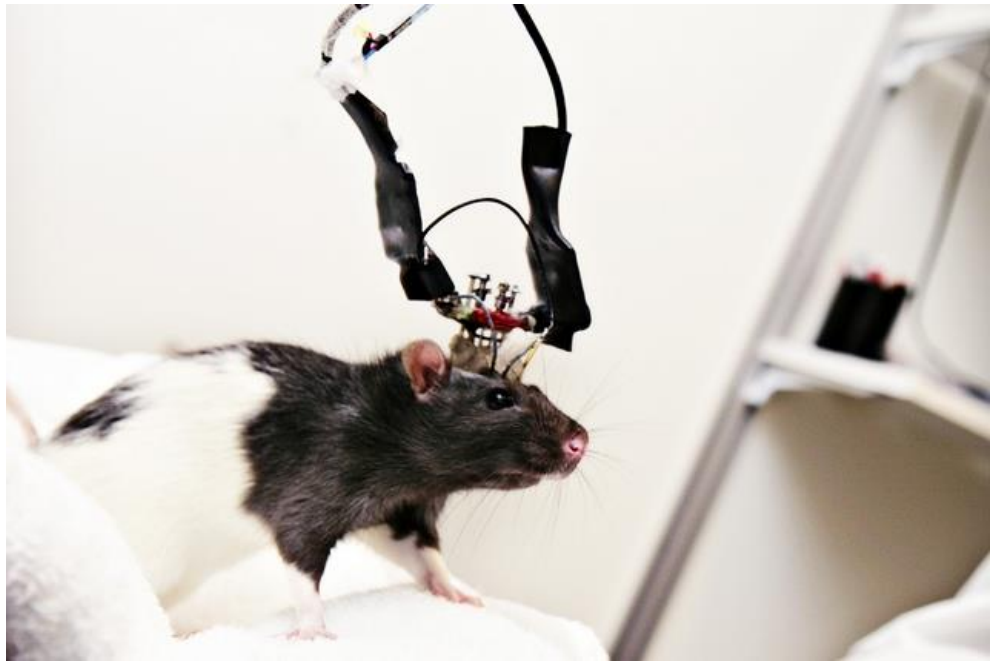
The Findings from a Rat's Brain

- Connections
- Functions
  - Spatial
  - Temporal
- Lateralization
- Building-Blocks



http://serious-science.org/genetic-manipulation-in-stem-cells-275

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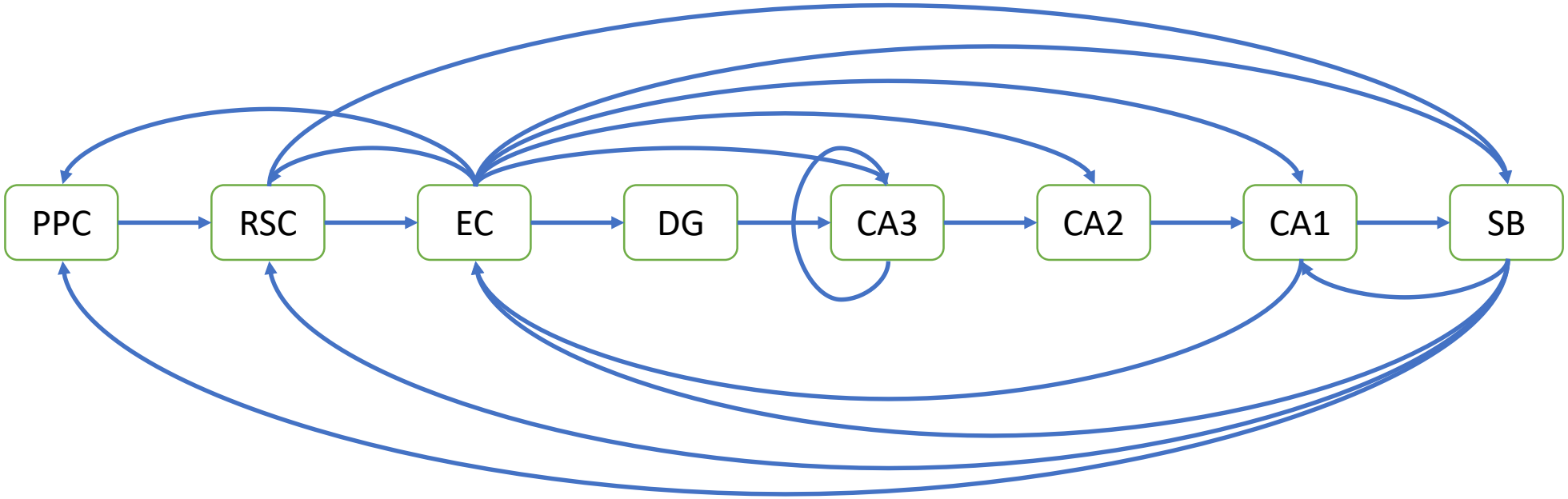
Connection



Posterior Parietal Cortex (PPC), Retrosplenial Cortex (RSC), Entorhinal Cortex (EC), Dentate Gyrus (DG), Cornu Ammonis 3 (CA3), Cornu Ammonis 2 (CA2), Cornu Ammonis 1 (CA1), Subicular Complex (SC).

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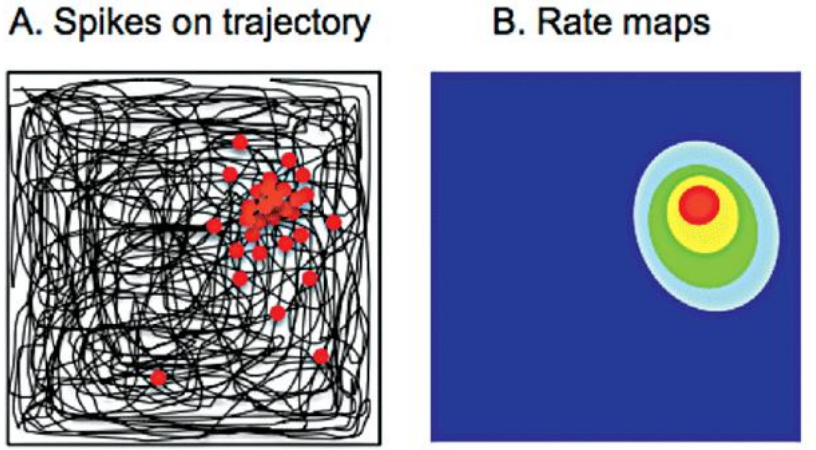
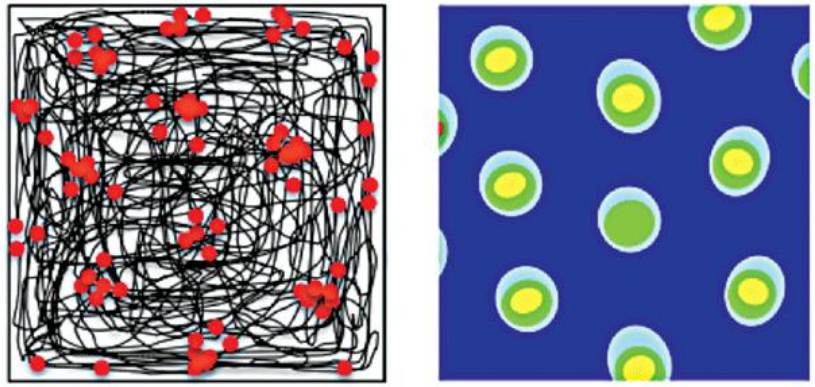
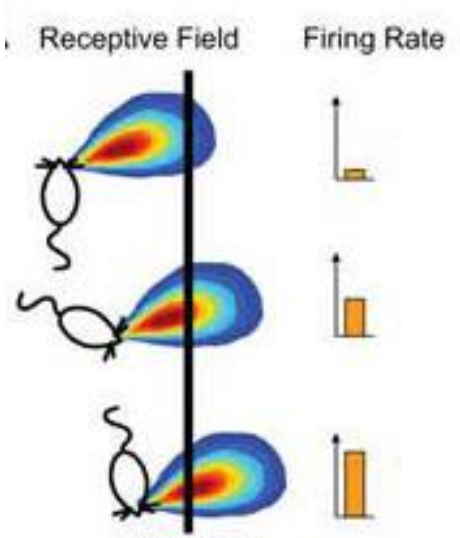
Functional Neuron Groups



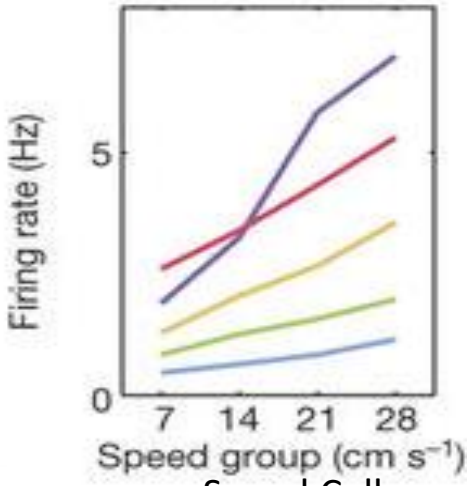
Place Cell



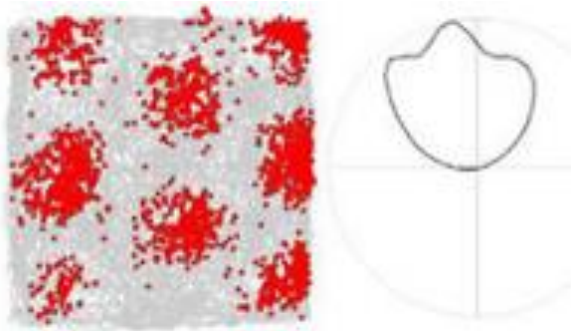
Grid Cell



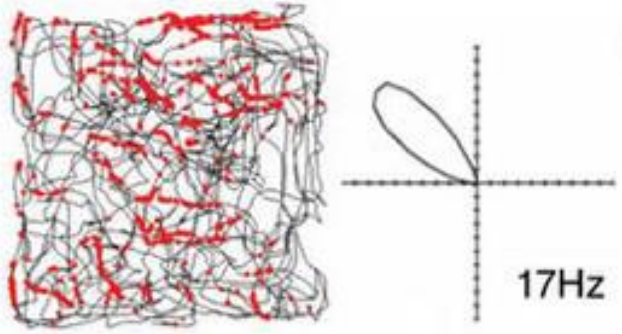
Boundary Vector Cell



Speed Cell



Grid x Head Direction Cell



Head Direction Cell

Image Source: E. I. Moser, M. Moser, N. Burgess, J. O'Keefe, et al.

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Functions

Allo/Ego-centric	Encoded Information	PPC	RSC	EC	DG	CA3	CA2	CA1	SC
Allo & Ego	Cue (x Head direction)	✓							
Route (Allo & Ego)	Route	✓	✓						
Ego	Head Direction	✓	✓	✓					✓
Ego	Head Direction x Self-motion	✓	✓						
Ego	Self-motion	✓	✓						
Allo & Ego	Multiple Stimuli		✓						
Ego	Speed		✓	✓				✓	
Allo	Grid			✓					✓
Allo & Ego	Grid x Head Direction			✓					✓
Allo	Border			✓					✓
Allo & Ego	Boundary Vector								✓
Allo	Object x Place			✓					
Allo	Ordor x place			✓					
Allo	Place cells				✓	✓	✓	✓	
Allo	Social Information						✓		

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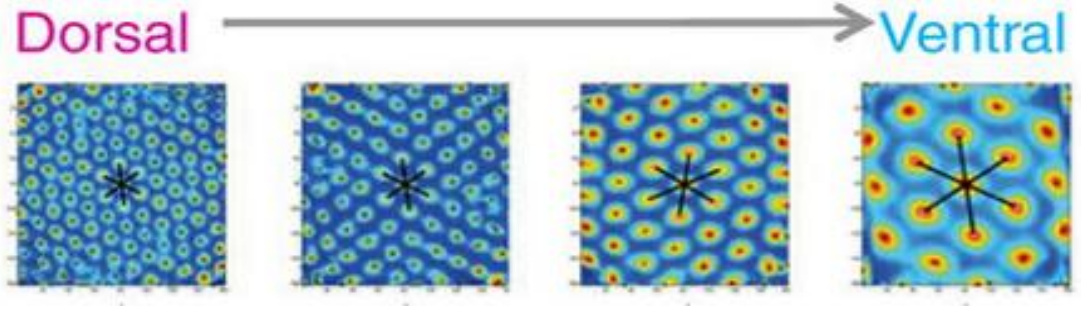
Spatial Scales

- Different groups of neurons encodes different scales



- Scale Independent

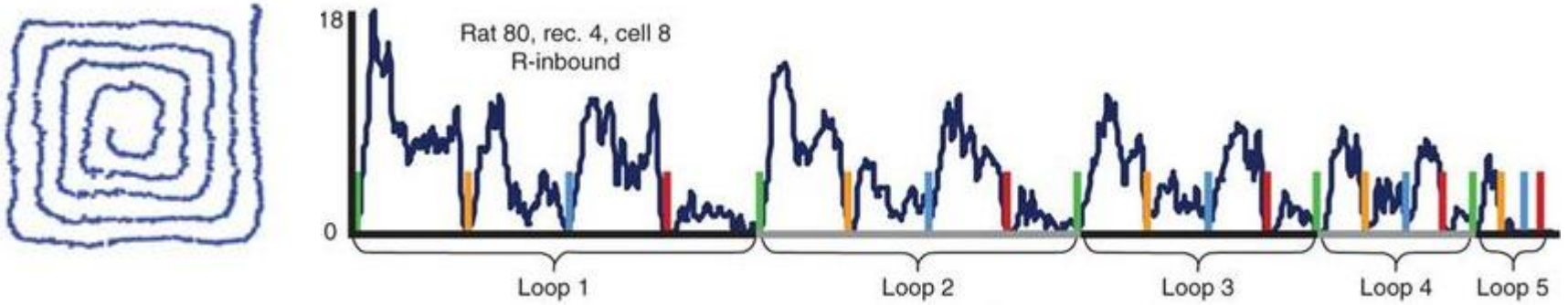


Image Source: H. Stensola, *Nature,* 2012*;* D. Nitz, *Nature,* 2012

Mystery Rhythms

- Theta Rhythms (4-7Hz)
  - Theta phase precession of place cells
  - Theta rhythm interference underlies grid cells
- Slow and Fast Gamma Rhythms (25-60 Hz; 60-100 Hz)
  - Modulate the synchronization between CA1 - CA3, or CA1 – MEC
  - Associated with long / short-path encoding
  - Slow gamma phase precession of place cells

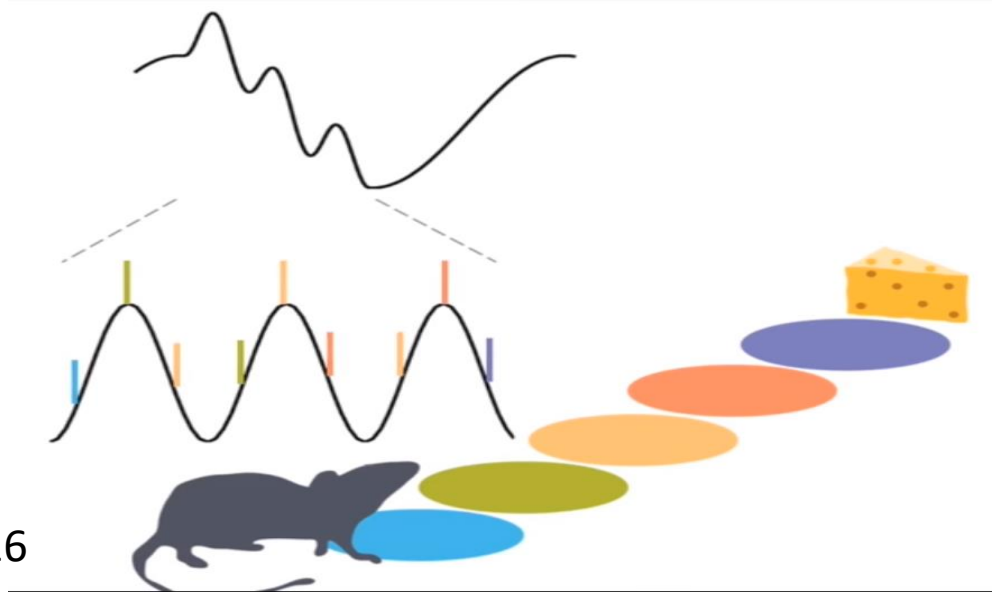


Image Source: C. Zheng, *Cell,* 2016

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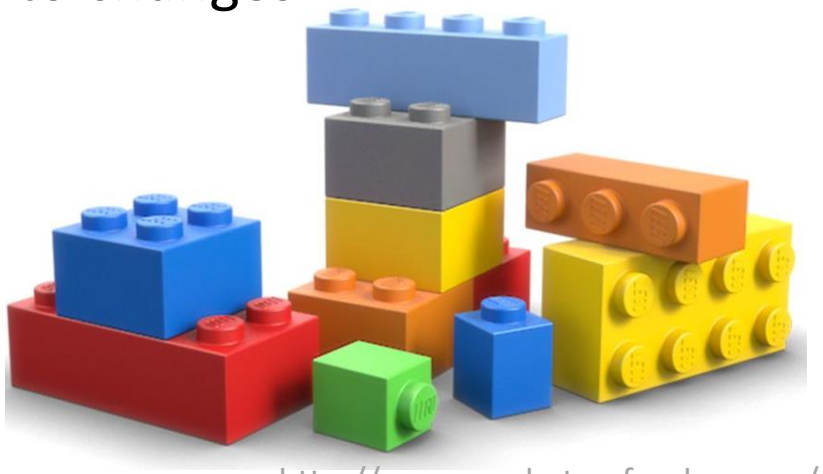
Building Blocks

- Rigid Building Blocks
  - Describing basic elements of spatial cognition
  - Can be light independent/scale independent/motion independent etc.
- Dynamic Building Blocks
  - Modulated by the rigid building blocks
  - Can undergo “partial remapping” corresponding to changes



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Lateralization – not obvious in HPC

	Left HPC	Right HPC
Human	Less involved in short term memory of object-location associations	More involved in short term memory of object-location associations
	London taxi drivers have smaller left hippocampus comparing to the right side	London taxi drivers have larger right hippocampus
	More involved in egocentric sequential information encoding	More involved in allocentric spatial information encoding
	Smaller left EC volume is found in patients who are progressing to Alzheimer than just in a stable mild cognitive impairment state	No difference
	No difference	Activity decreased when retrieving more remote autobiographical memories, and more involved in recollective autobiographical memories retrieval
Rodent	Left CA3 silencing impaired long-term memory	Right CA3 silencing does not impair long-term memory
	Microinjecting ANG II (a type of hormone) to the left hippocampus increased learning and memory performance more	Increased less in learning and memory performance when ANG is injected
	The left DG is more active during object exploration comparing to the right one	The right DG is less active in object exploration comparing to the left one
Avian	Domestic chicks with damaged left hippocampus could still find the food buried in the center of the arena given geometric cues	Domestic chicks with damaged right hippocampus could not find the food buried in the center of the arena given geometric cues

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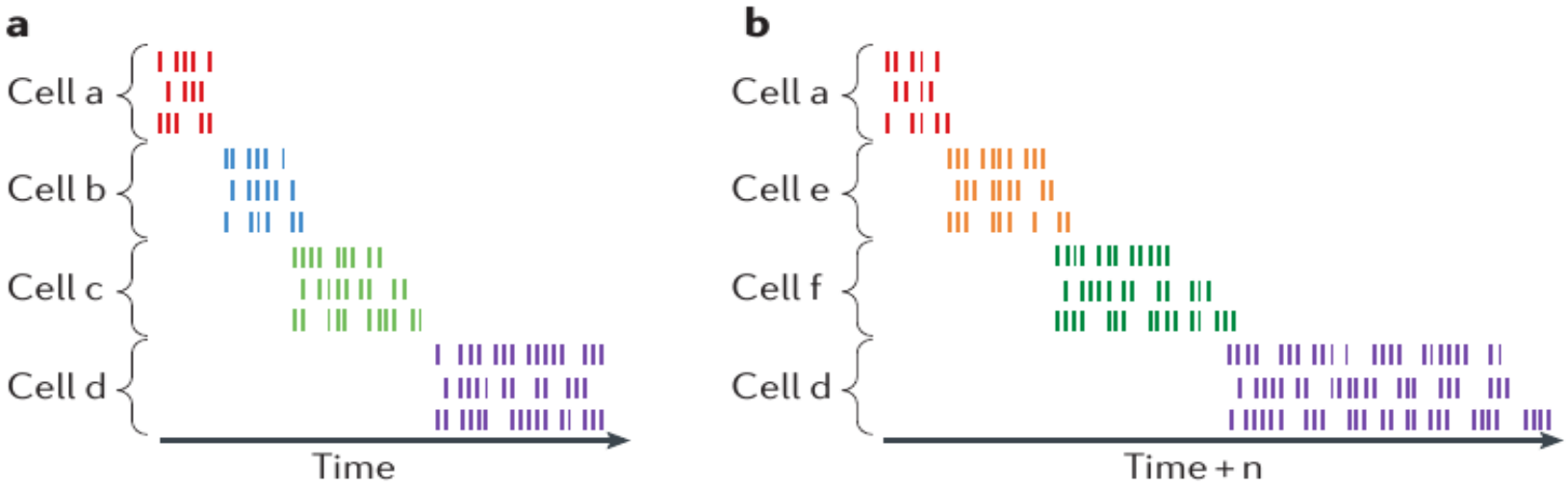
Time Representation

- Time Cells



- Firing Timings
- Brain Rhythms
- CA2 ?

Image Source: H. Eichenbaum, *Nature,* 2014

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The Attempts to Build an Artificial Rat

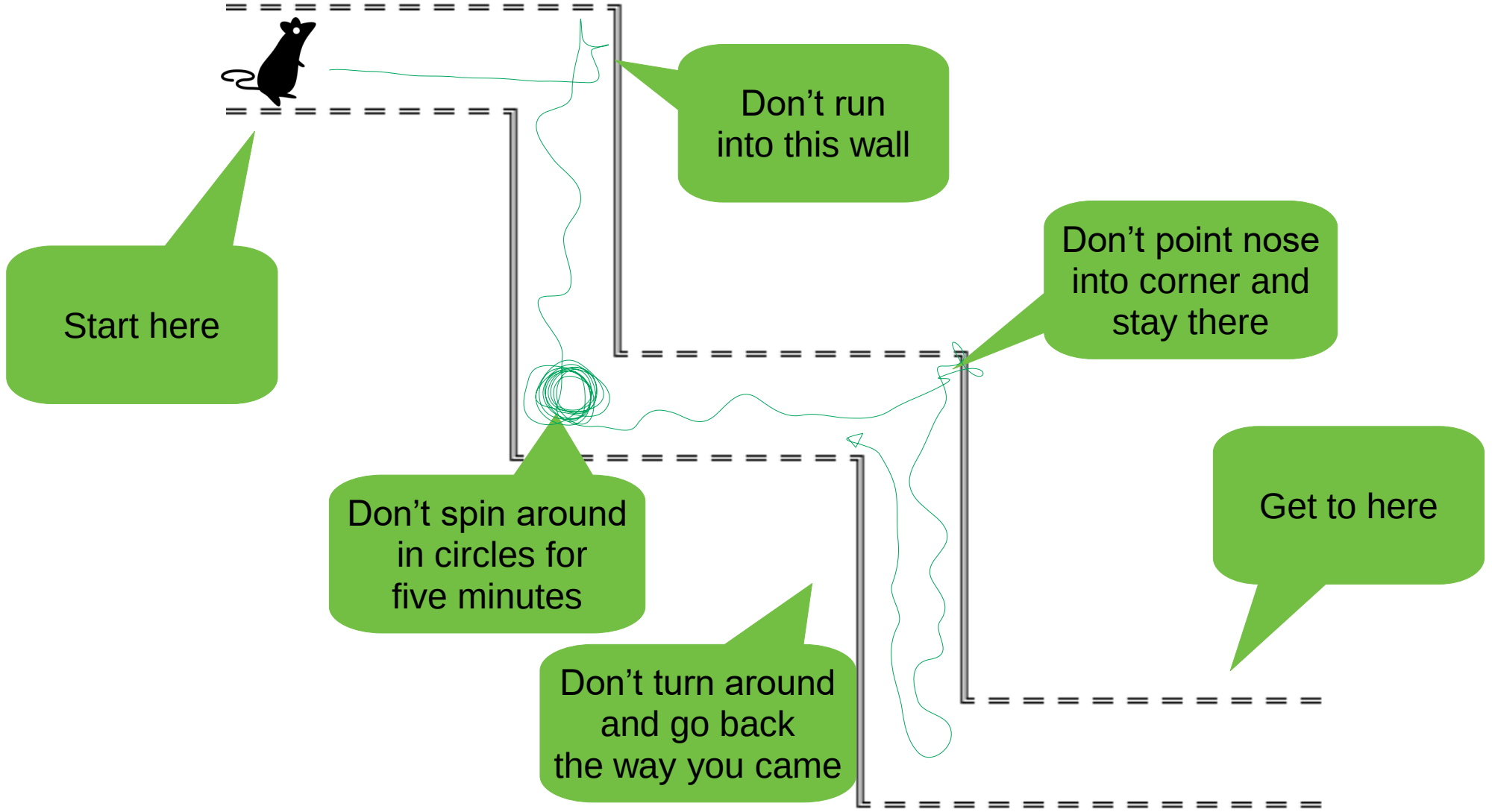

Image Source: Alex Rose, *ECS Talk,* 2018

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Training & Testing

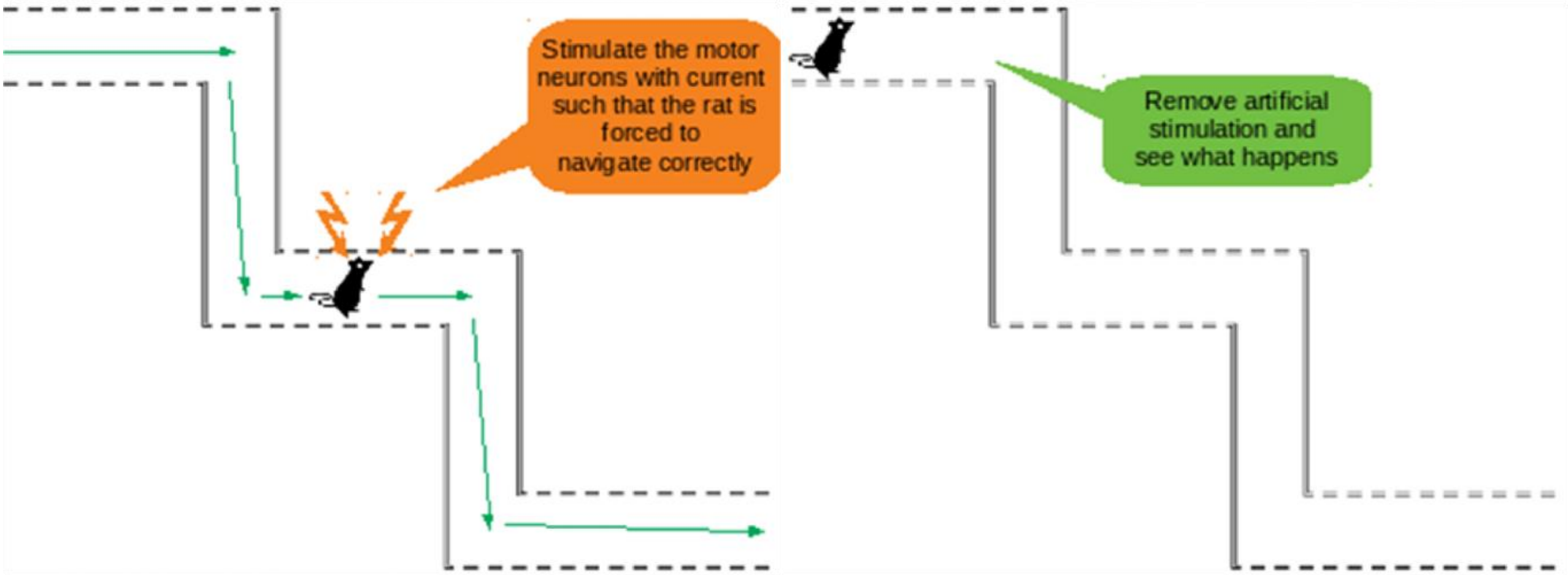

Image Source: Alex Rose, *ECS Talk,* 2018

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CARLsim3

- Izhikevich model + Spike Timing Dependent Plasticity + GPU

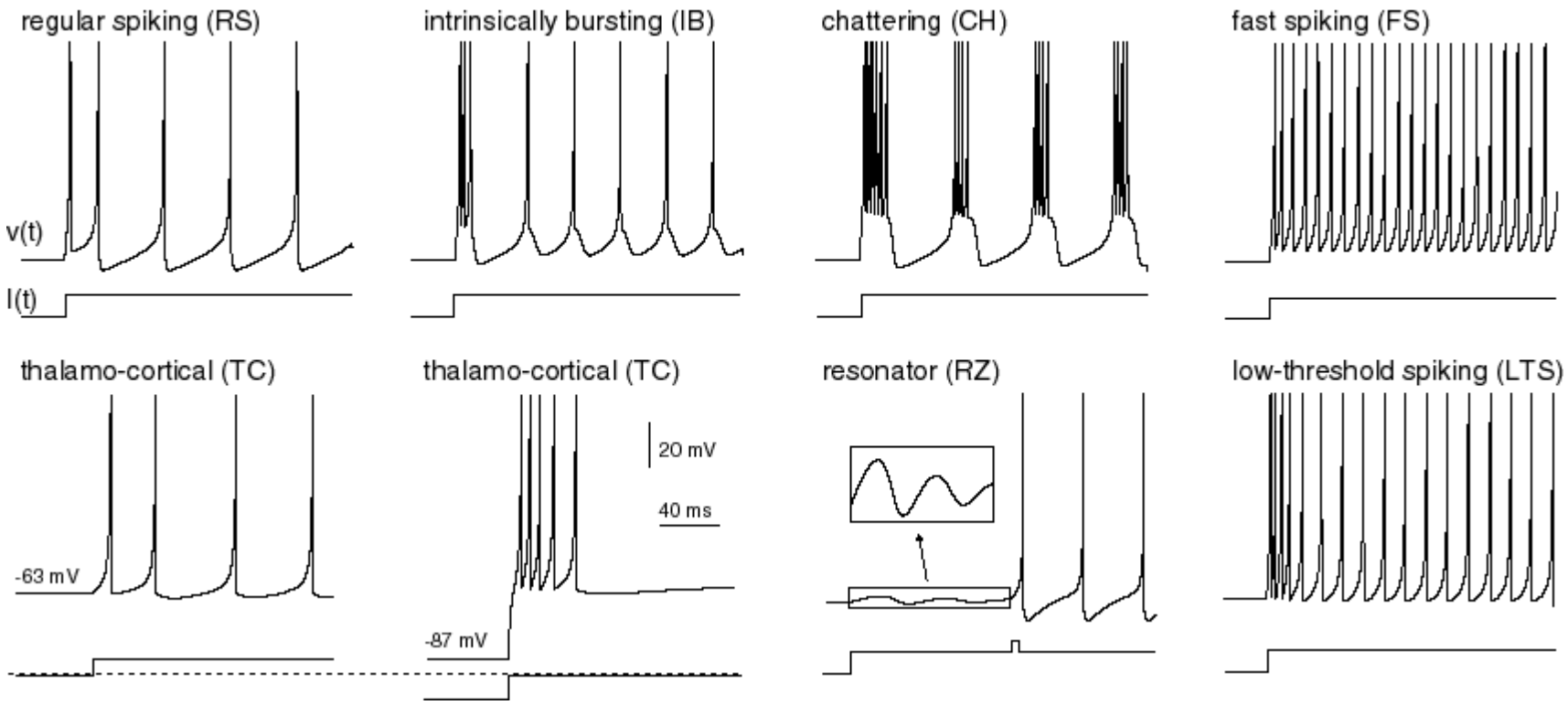

Image Source: E.M. Izhikevich, *IEEE Transactions on Neural Networks*, 2004

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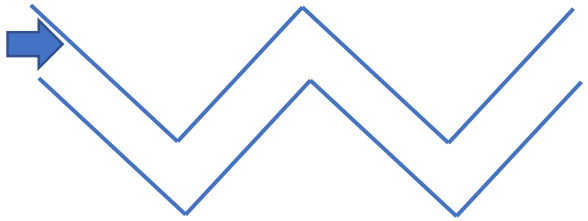
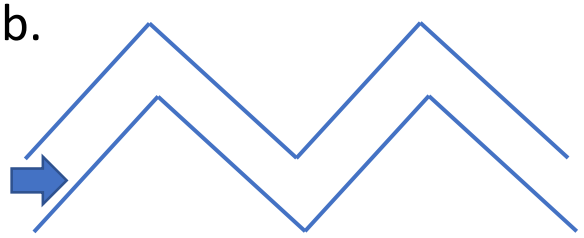
Mazes

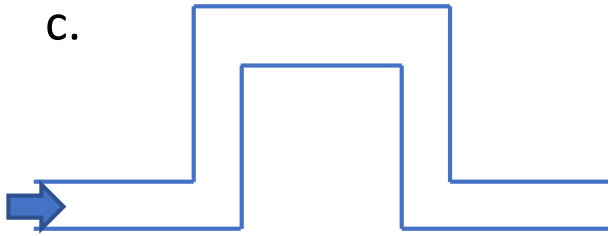
a.



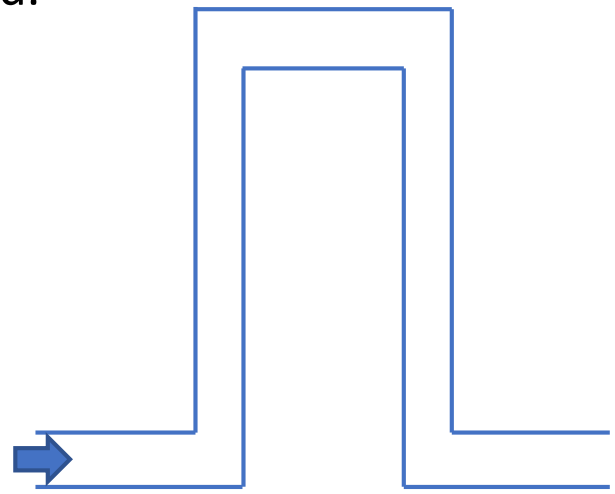
b.



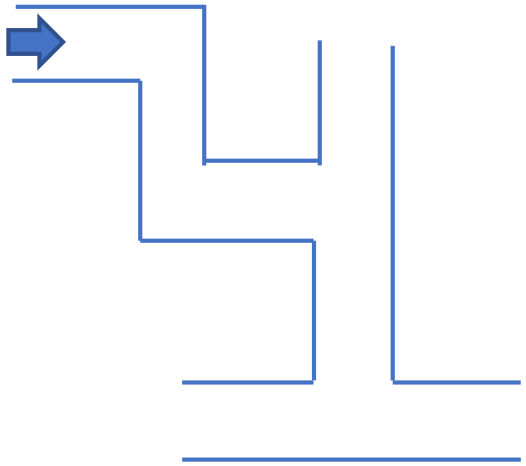
c.



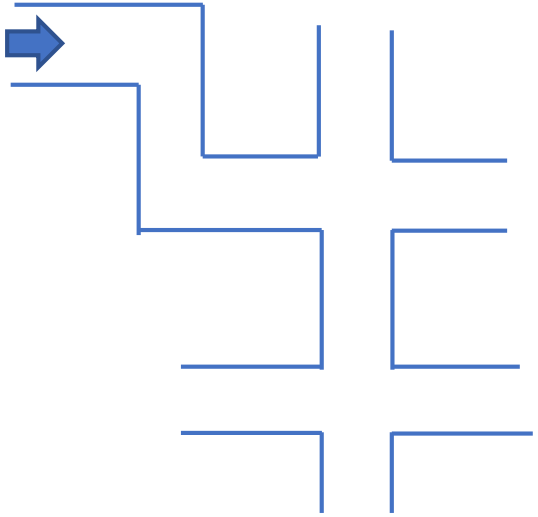
d.



e.

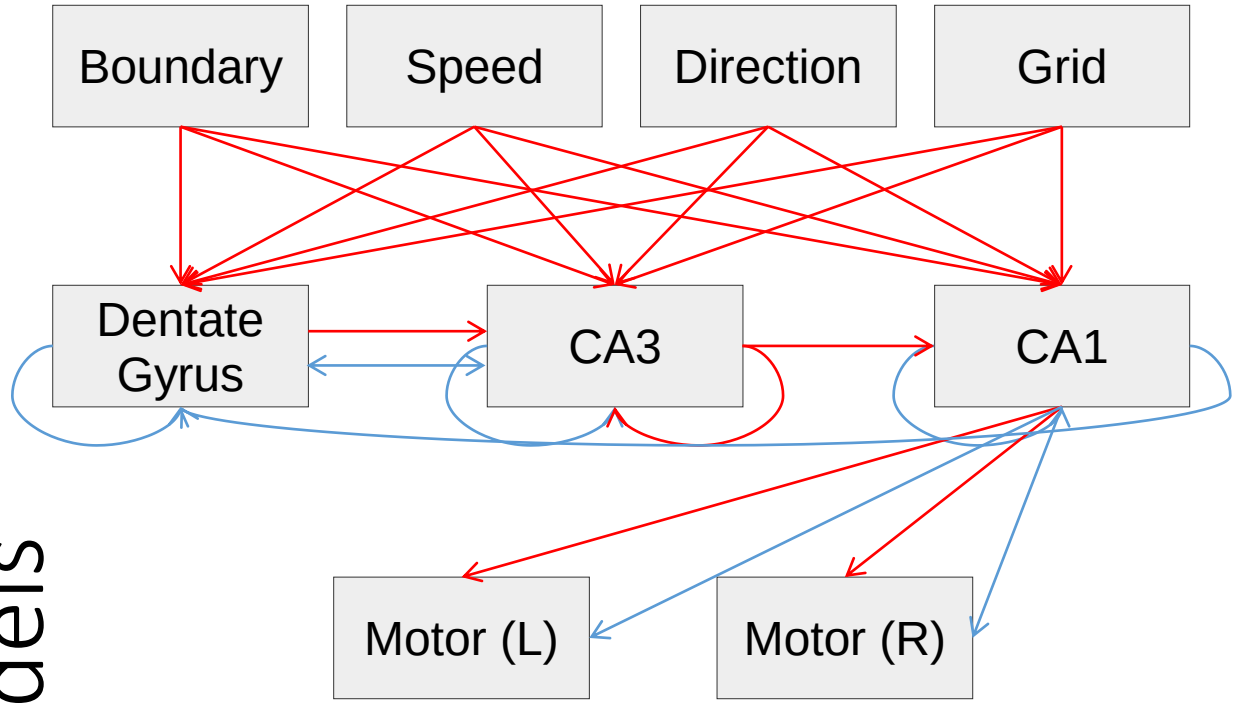


f.

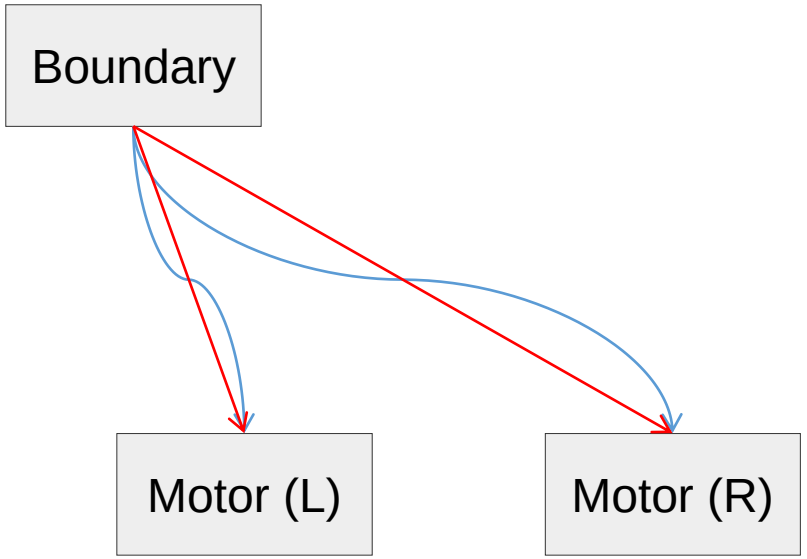


Models

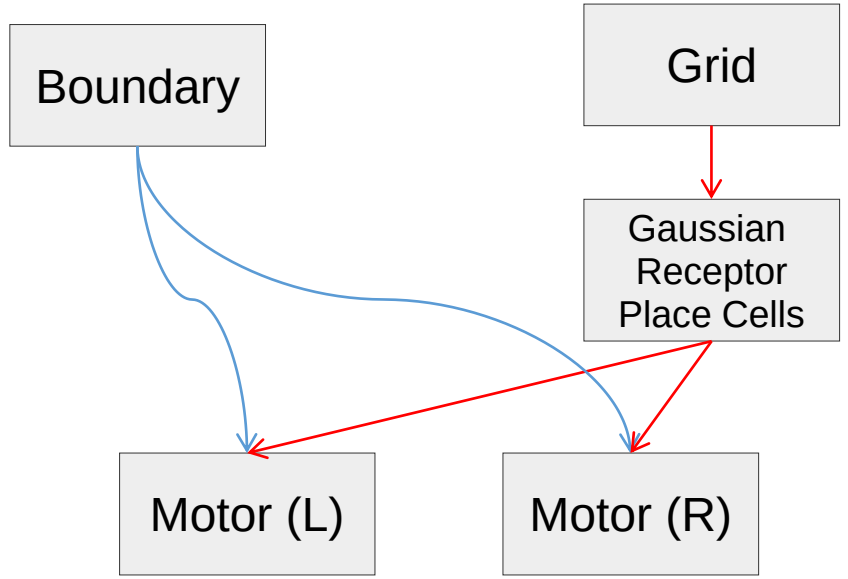
a.


Boundary
Speed
Direction
Grid
Dentate Gyrus
CA3
CA1
Motor (L)
Motor (R)

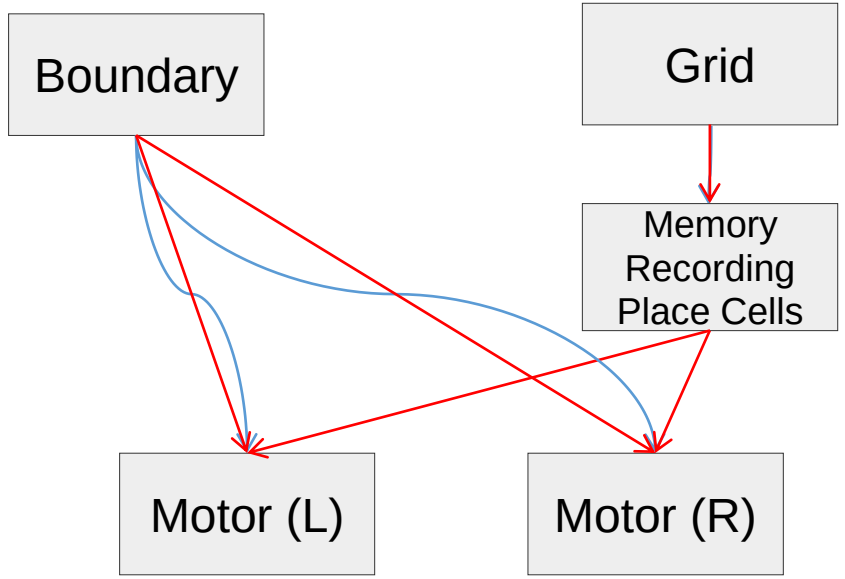
b.


Boundary
Motor (L)
Motor (R)

c.


Boundary
Grid
Gaussian Receptor Place Cells
Motor (L)
Motor (R)

d.


Boundary
Grid
Memory Recording Place Cells
Motor (L)
Motor (R)

Deep Neural Networks for Grid Cells

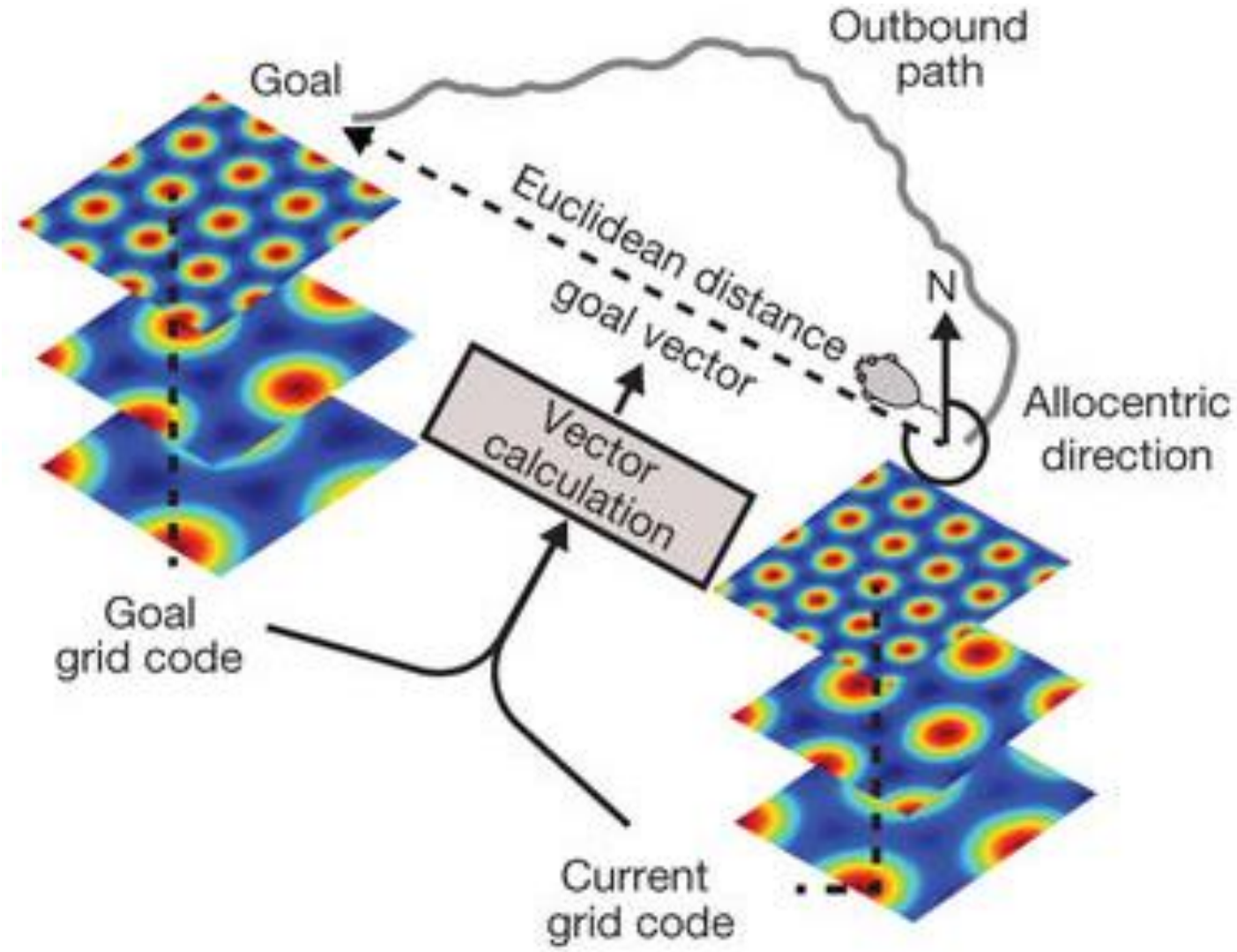


Image Source: DeepMind & UCL Team, *Nature*, 2018

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Conclusions

- Results:
  - Building-block mechanism ✓
    - Boundary cells, grid cells, place cells
  - Spiking Neural Network ✓

- Next:
  - Time representation
  - Lateralization
  - Other factors such as emotions

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Thanks !

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Models

- Izhikevich Model:

$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

if $v = 30$ mV,
then $v \leftarrow c$, $u \leftarrow u + d$

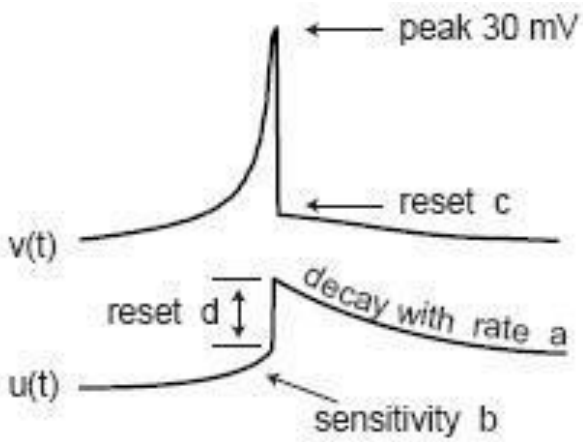


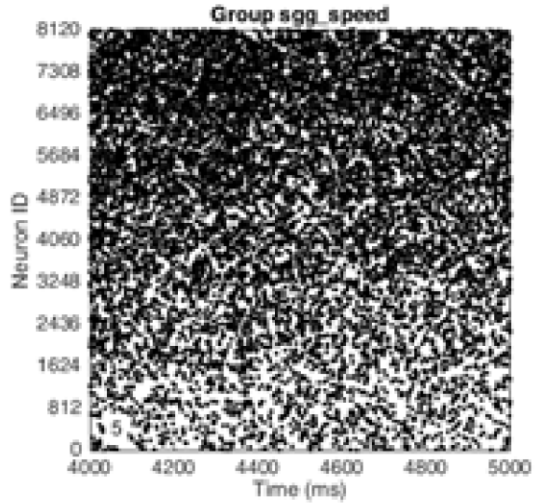
Image Source: E.M. Izhikevich, *IEEE Transactions on Neural Networks*, 2004

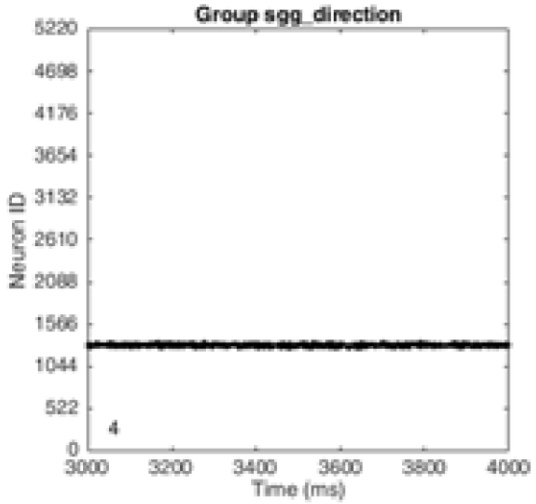
- STDP:

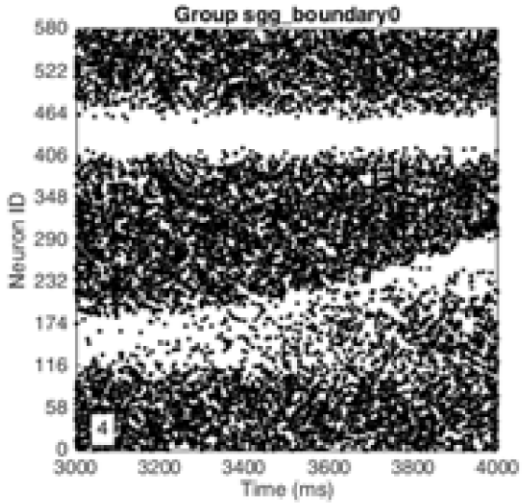
$$\frac{du}{dt} = \frac{-u}{STP\_tau\_u} + STP\_U(1 - u^-)\delta(t - t_{spk}) \quad (1)$$
$$\frac{dx}{dt} = \frac{1 - x}{STP\_tau\_x} - u^+ x^- \delta(t - t_{spk}) \quad (2)$$
$$\frac{dI}{dt} = \frac{-I}{\tau_S} + Au^+ x - \delta(t - t_{spk}) \quad (3)$$

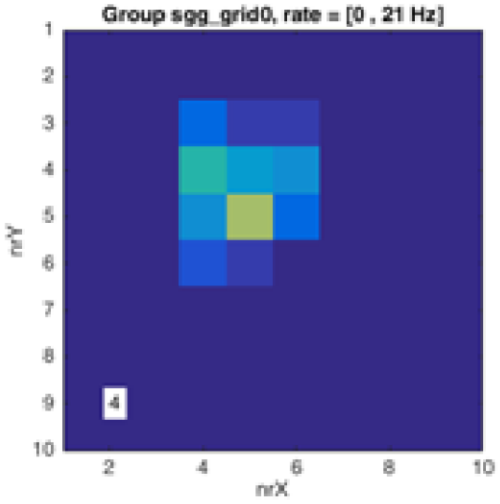
Image Source: CARLsim3 User Guide, UCI, 2016

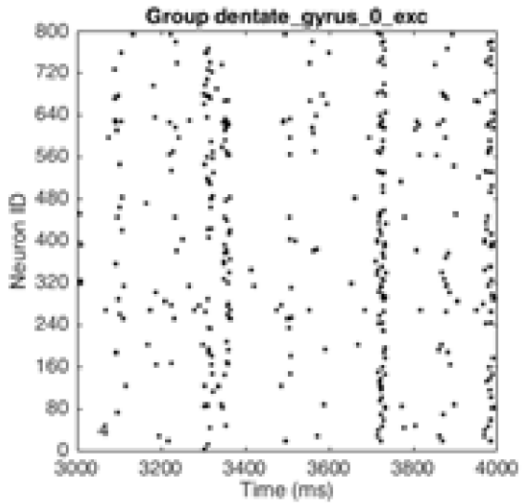
Complex Structure

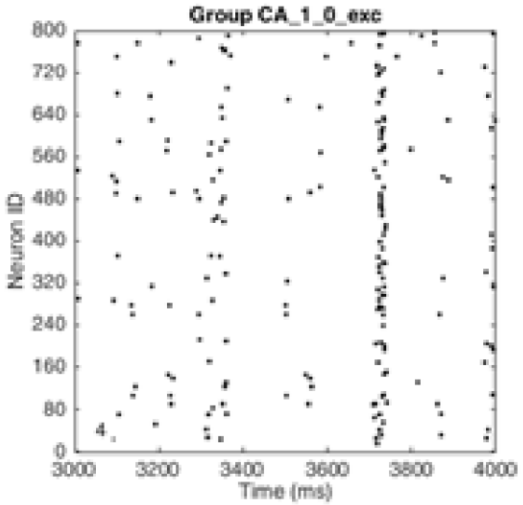


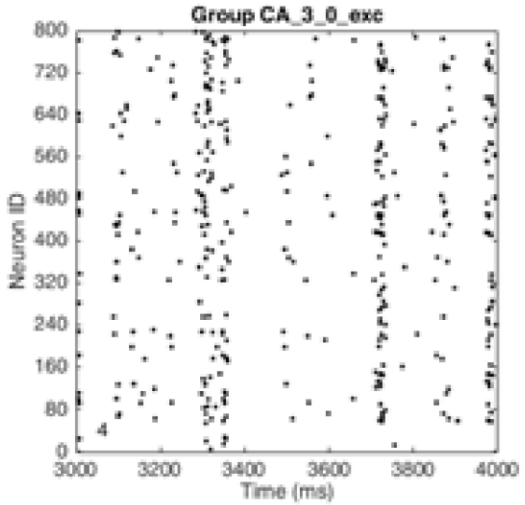












Spiking Boundary