SMU/RTG Research Experience for Undergraduates
June 21 – July 16, 2021

Poster:

SMU-Math Research Experience for Undergraduates (SMU-REU): Summer 2021

The Department of Mathematics at SMU invites applications for two consecutive two-week research and training experiences covering topics in mathematical and computational neuroscience (REU 1) and dynamics in complex systems (REU 2).

REU 1: Computation-enabled Investigations into Neural Circuits
Dates: June 21-July 2, 2021
Faculty Mentors: Andrea Barreiro and Kathryn Hedrick
Research projects using experimental data from partner labs in the UT Southwestern Department of Neuroscience.

REU 2: Dynamics in complex systems
Dates: July 6-16, 2021
Faculty Mentors: Binh Minh Tran and Alejandro Aceves
Research projects will center on applications in nonlinear optics and general wave phenomena.
We anticipate some projects will be in collaboration with National or private Laboratories.

Review of applications will begin on **March 26, 2021**: later applications will be considered as space permits.

To more information, contact abarreiro@smu.edu.

To participate, students must be US citizens or permanent residents and must not have completed their undergraduate degree before January 2021. Selected students will receive a stipend of $1,200 per two-week session, plus up to $600 towards travel to Dallas as well as accommodation. We encourage applications from women and other groups traditionally underrepresented in mathematics. Students can apply to one or both REUs.

To submit a complete application, please submit the following items via e-mail to abarreiro@smu.edu:

- One letter of recommendation, preferably from a mathematics professor. Letters may be sent directly from the individuals who are writing the letters.
- An essay of 250-500 words describing your research interests, educational interests, and professional plans.
- An academic transcript (unofficial or official)
- Students should indicate which REU she/he is applying for (REU 1, REU 2, Both)

I. Program:

REU 1: Computation-enabled Investigations into Neural Circuits

<u>Schedule</u>
Week 1: Tutorials
Morning session: 9-12
Afternoon session: 1:30-5-ish
Both: 1 hr lecture, 1 hr time to work on assignment, 30 mins discussion, 30 mins buffer

Unless specified otherwise: all events take place in 120 Clements Hall

Date/time	***Presenter***	***Topic***
Monday (June 21)		
9am-9:45am		Intros, COVID briefing, other administrative
10am-12pm	Barreiro/Hedrick	Intro to research/computational neuroscience
1:30-3:30pm	Pfeiffer	Place cell encoding
4-5 pm (or later?)	Walton	Matlab tutorial
Tuesday		
9am-12pm	Barreiro	Data analysis of spikes, Poisson process
1:30-5pm	Hedrick	Rate models, attractor networks
Wednesday		
9am-12pm	Barreiro	Basic statistics: hypothesis tests, P-P plots
1:30-5 pm	Hedrick	Place cell sequences: theta sequences and replay
Thursday		
9am-12 pm	Barreiro	Cell assembly detection algorithm, previous results
1:30pm-5pm	Hedrick/Hetzel	Synaptic plasticity and STDP
Friday		
9am-12pm	Barreiro	Discussion of possible project: Adapting the CAD algorithm for place cell sequences
1:30-5pm	Hedrick	Discussion of possible project: adapting network model to generate reverse replay events

Week 2: Research Project

Date/time	***Presenter***	***Topic***
Monday (June 28)		
10am-12pm		TAs available
2:30-3:30 pm		Advisor meeting; Group 1 (Finalize paper)
3:30-4:30 pm		Advisor meeting; Group 2 (Finalize paper)
Tuesday		
10am-12pm		TAs available
2:00pm		Pfeiffer Lab Tour (UTSW)
3:00-4:00pm		Advisor meeting: Group 1
4:00-5:00pm		Advisor meeting: Group 2
Wednesday		
10am-12pm		TAs available
2:00-3:0pm		Advisor meeting: Group 1
3:00-4:00pm		Advisor meeting: Group 2
4-5pm	Office of Engaged Learning	**Ways of Presenting: Papers, Presentations, and Elevator Pitches (**Harold Clark Simmons Hall, 217)
Thursday		
10am-12 pm		TAs available
2:30-3:30pm		Advisor meeting: Group 1
3:30-4:30pm		Advisor meeting: Group 2
Friday		
9am-12pm	Students	Group Presentations

REU 2: Dynamics of complex systems

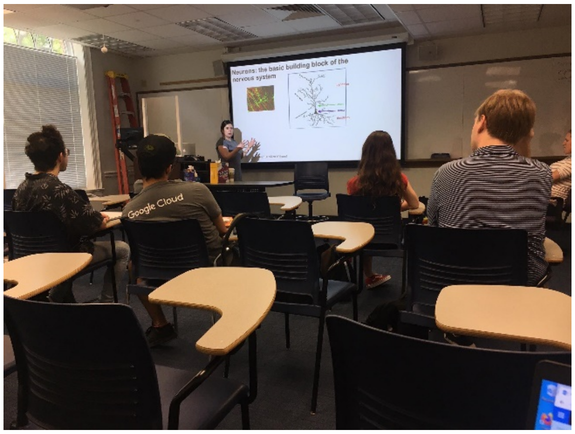
<u>Schedule</u>
Week 2: Tutorials
Morning session: 9-12
Afternoon session: 1:30-5-ish
Both: 1 hr lecture, 1 hr time to work on assignment, 30 mins discussion, 30 mins buffer

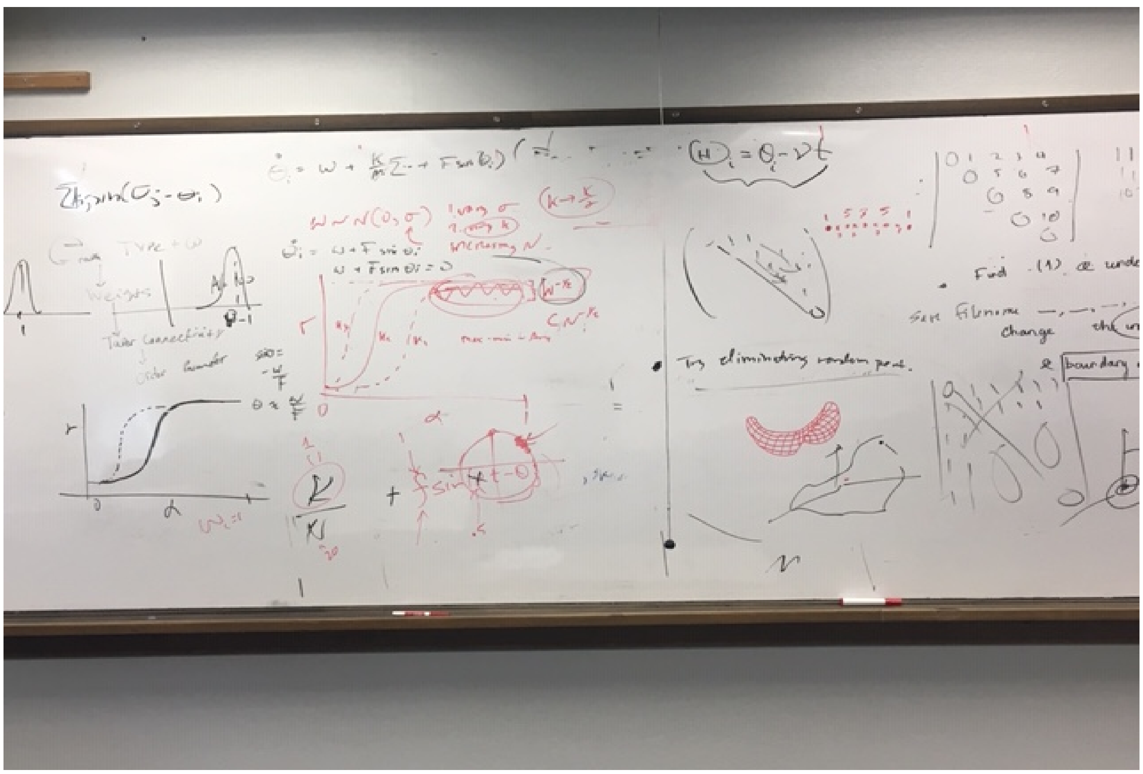
Unless specified otherwise: all events take place in 120 Clements Hall

Date/time	***Presenter***	***Topic***
Tuesday (July 6)		
9am-9:45am		Intros, COVID briefing, other administrative
10am-12pm	Tran/Aceves	Intro to research topics
1:30-3:00pm	Aceves	Modeling in photonics
4-5 pm	Evans (student)	Matlab tutorial
Wednesday		

9am-12pm	Tran	Simulation of waves on a string
1:45-5pm	Aceves	Dynamics of coupled oscillators. The Kuramoto model.
Thursday		
9am-12pm	Tran	Formulating a recursive algorithm
1:30-5 pm	Aceves/Parker	Power grid model/FPU models I
Friday		
9am-12 pm	Tran	Implementation
1:30pm-5pm	Parker	FPU models II
WEEK 2	Research projects	
Date/time	***Presenter***	***Topic***
Monday (July 12)		
9am-9:30AM	REU students	Research proposals
9:30-10:30AM	REU team	Research proposals
10:30AM – noon	Tran meeting	Fluids
2:00-3:00 pm		Meet of research teams
3:30-4:00 pm		Summary of progress
4:00-5:30 pm	**Dr. Gowri Srinivasan Deputy Director, Physics Division LANL. Mr. Jonathan Lindbloom SMU Math major.**	**Internship opportunities at the Los Alamos National Laboratory**
Tuesday (July 13)		
9am-10am		Tran meeting
10am-noon	Research	TA support (Tyler, Sabrina)
2:00pm – 3PM	Research	Working groups
3:30-4:00pm	Research	Summary of work progress
4:00-5:00pm	Research	Meeting with REU team
Wednesday (July 14)		
9am-10am		Tran meeting
10am-noon	Research	TA support
2:00-3:0pm	Research	Working groups
3:00-4:00pm	Research	Meeting with REU team
4-5pm	Dr. Ken Yamamoto	**Patterns and geometry in nature: From flowers, sea slugs, to robots**
Thursday (July 15)		

10am-12 pm	Research	TAs available
2:00-3:300pm	Research	Advisor meeting: Group 1
4:00-5:00pm	Research	Working with REU ream
Friday (July 16)		
9am-12pm	Students	Group Presentations





II. Sample Lecture (from session 1)

Introduction to Computational Neuroscience

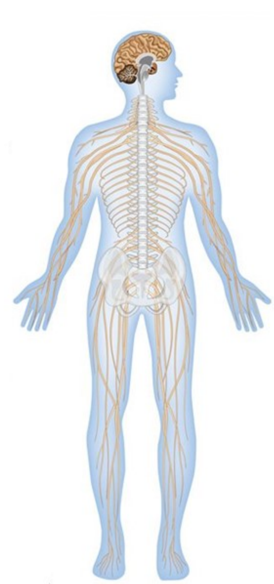
SMU/RTG REU 1: Computation-enabled Investigations into Neural Circuits

Andrea Barreiro and Kathryn Hedrick

June 21, 2021

What is neuroscience?

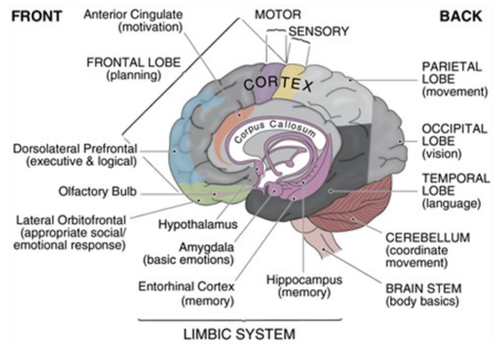
- Study of the nervous system
- And/or any behavior connected to the nervous system
- Related disciplines:
  - Biology
  - Psychology/Cognitive science
  - Mathematics and Computer Science
- Many sub-fields:
  - Cellular, molecular, behavioral, developmental, cognitive, social, translational/clinical…
  - Mathematical/computational

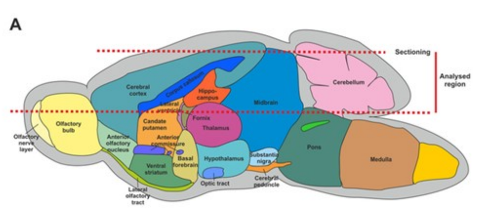


Mostly we worry about the brain

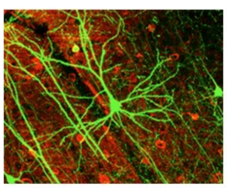
- This is where all the interesting stuff happens!
- Distinct functional regions
- Many structures and functions conserved between species

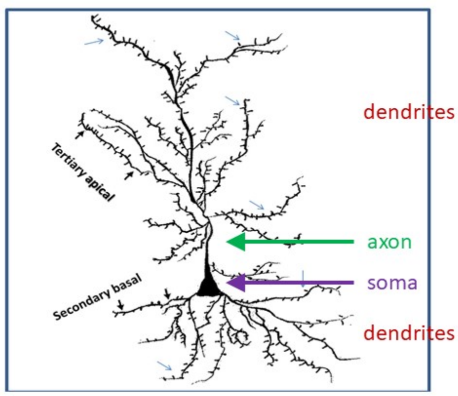
- Two types of cells: neurons and glia
- A human brain has ~ 10^{11} neurons





Neurons: the basic building block of the nervous system

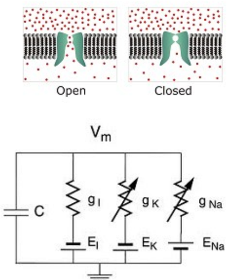




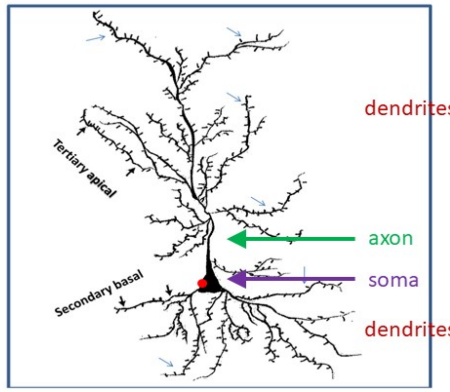
Remember: you have 100 billion of these!

Neurons: the basic building block of the nervous system

- Lipid cell membrane maintains an electrical charge
- Membrane is filled with ***voltage-gated ion channels***
- A patch of membrane can be modeled much like an electric circuit
- If the membrane becomes sufficiently ***depolarized***, a rapid depolarization called an ***action potential*** or ***spike*** occurs

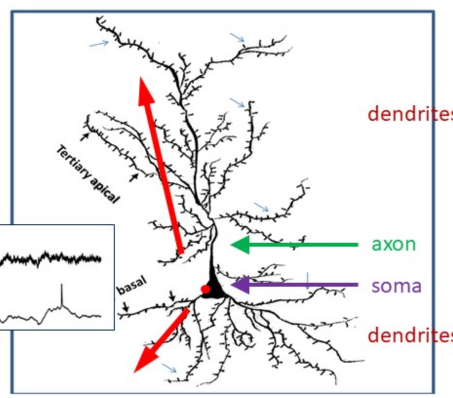


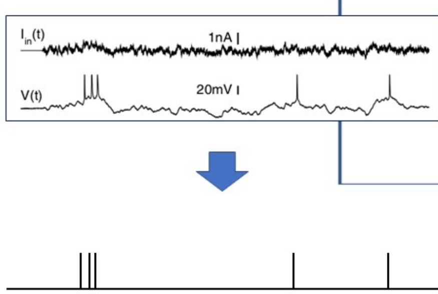
equivalent RC circuit
(g=1/R)



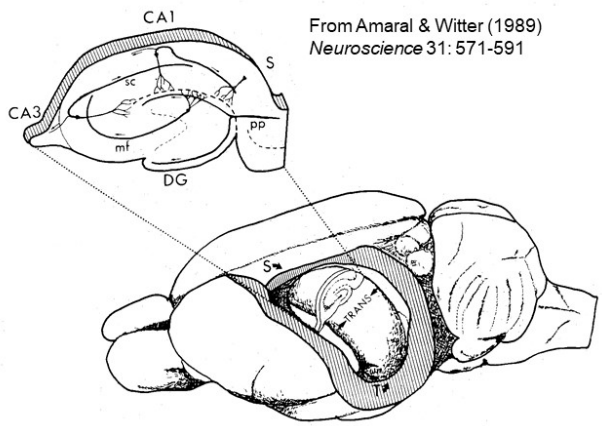
Neurons: the basic building block of the nervous system

- The action potential is capable of fast travel throughout the neuron
- This activates connections between neurons or **synapses.**
- Because of the “all-or-nothing” nature of spike transmission, we idealize spikes as a sequence of discrete events, completely defined by the times at which they occur.



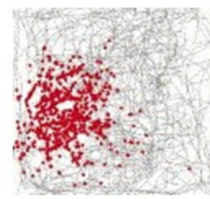


Hippocampus and spatial memory

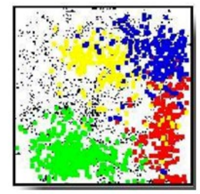


From Amaral & Witter (1989)
Neuroscience 31: 571-591

Place Cells in the CA1/CA3



One Place Cell

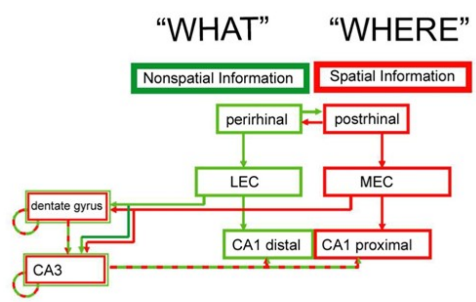


Four Place Cells

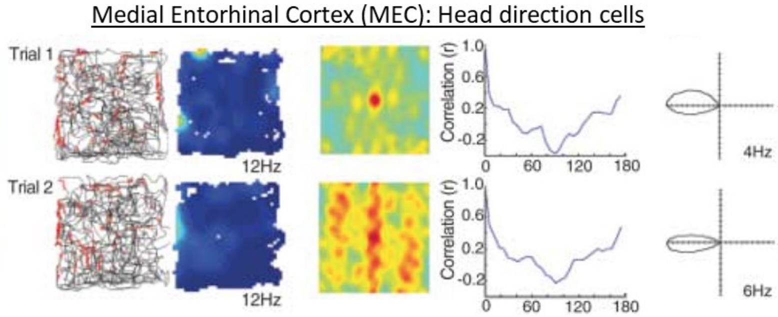
“The hippocampus is the core of a neural memory system providing an objective spatial framework within which the items and events of an organism’s experience are located and interrelated.”

J. O’Keefe & L. Nadel (1978) *The Hippocampus as a Cognitive Map* Oxford University Press, p. 1.

Cells involved in the brain’s “cognitive map”

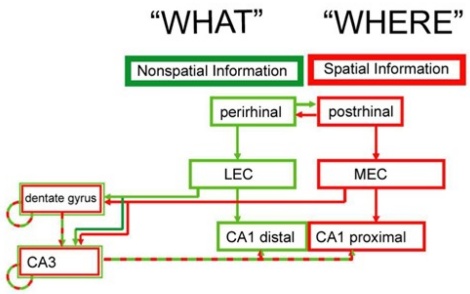


<u>Medial Entorhinal Cortex (MEC): Head direction cells</u>

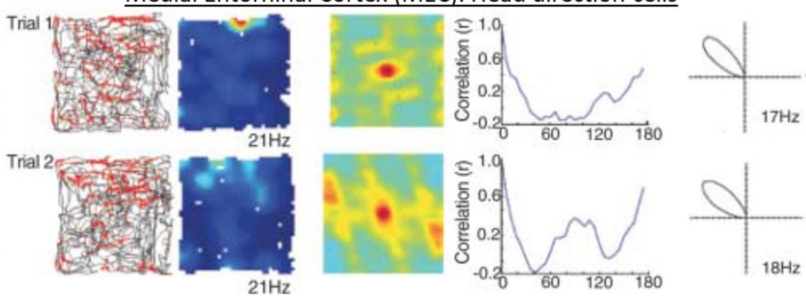


(Sargolini et al., 2006)

Cells involved in the brain's "cognitive map"



Medial Entorhinal Cortex (MEC): Head direction cells



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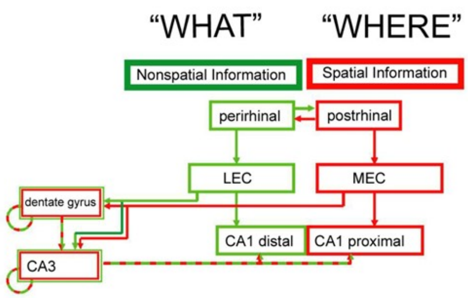
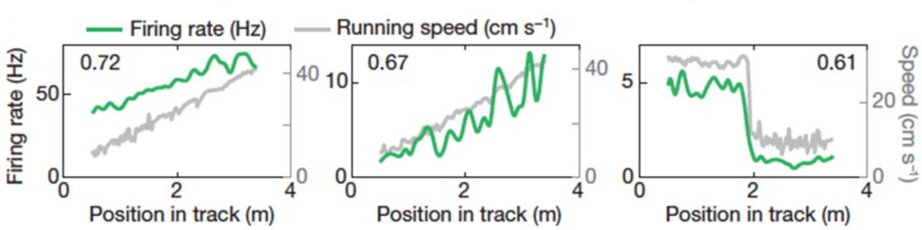
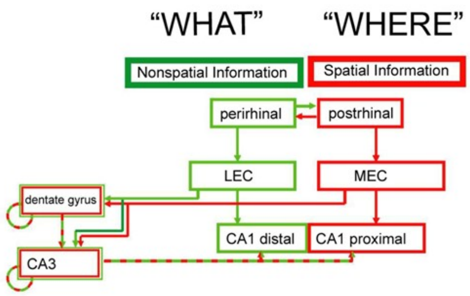


Medial Entorhinal Cortex (MEC): Speed cells

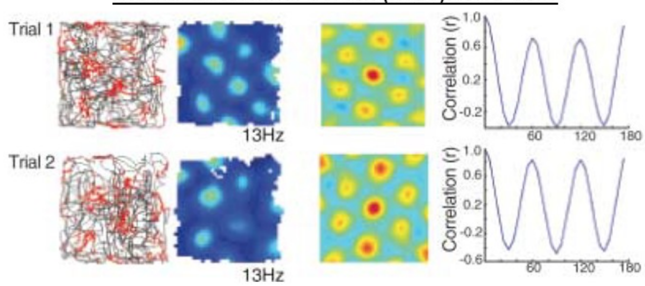


(Sargolini et al., 2006)

Cells involved in the brain’s “cognitive map”

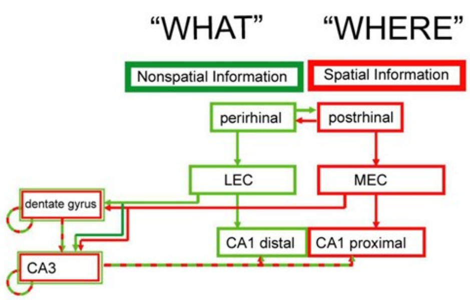


Medial Entorhinal Cortex (MEC): Grid Cells



(Sargolini et al., 2006)

Cells involved in the brain’s “cognitive map”



Partial Summary:

LEC (Lateral Entorhinal Cortex)
- Encode objects

MEC (Medial Entorhinal Cortex)
- Head direction cells
- Speed cells
- Grid cells

Hippocampus
- Place cells in CA1 and CA3 subregions
- CA3: recurrent connections important for memory
- CA1: output of the system

A Few Big Questions in Neuroscience

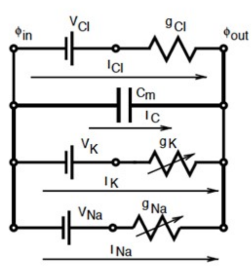
- How do the cells work together for spatial memory and navigation?
- What is the functional role of a given neural network or cell type?
- What are the mechanisms that cause cells to encode a variable?
- How does the brain learn a new environment or adapt to a changing environment?
- How does the brain use these cells for internal computations, like path integration, navigation, and learning the location of a reward?

Computational neuroscience: Modeling

What is a computational model?

- Set of equations or algorithms that resemble certain aspects of neural activity

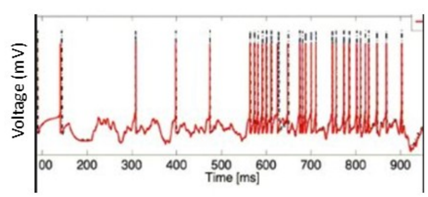
Example: Hodgkin and Huxley Model



$$C_m V'(t) = -\overline{g}_{Na} m^3 h (V - V_{Na}) - \overline{g}_K n^4 (V - V_K) - g_{Cl}(V - V_{Cl}) + I_{stim}/A$$

For any gating variable $z = m, h, n$: $\quad z(t;V) \to z_\infty(V) = \alpha_z(V)\tau_z(V)$

$$\tau_z(V) z'(t) = z_\infty(V) - z(t) \qquad \text{with time constant } \tau_z(V) = \frac{1}{\alpha_z(V) + \beta_z(V)}$$



Computational neuroscience: Modeling

What is the difference between research in computational neuroscience and artificial intelligence?

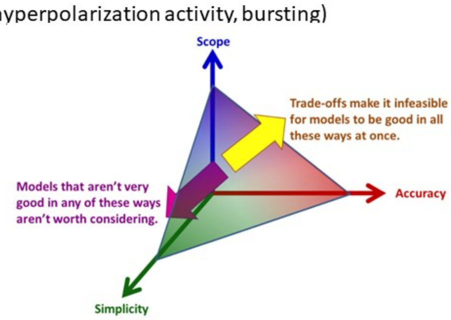
- AI: Goal oriented – Develop algorithms motivated by the brain that can perform computations the brain is very good at
- Computational neuroscience: Empirically oriented – Develop models to help better understand the brain

How can a model help us better understand the brain?

- Hodgkin and Huxley model: interplay of ionic currents (e.g. after-hyperpolarization activity, bursting)
- Test hypotheses: what mechanisms can reproduce data?
- Make testable predictions: partnership with experimentalists

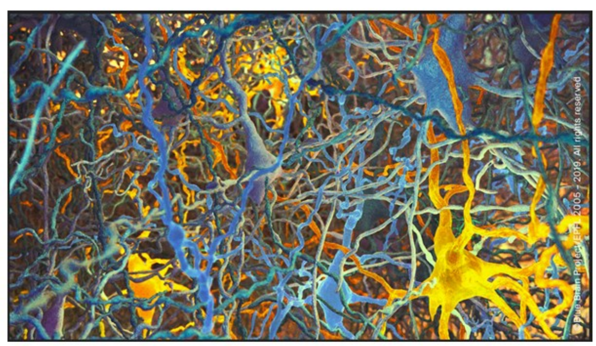
Considerations:

- Scope vs. accuracy vs. simplicity



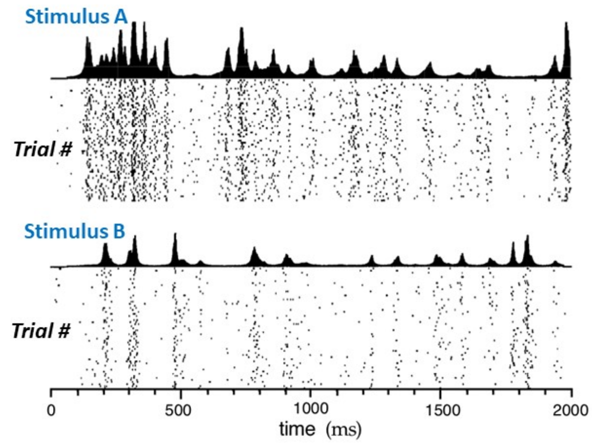
Example: Modeling single neurons vs. neural networks

- Single neuron $\xrightarrow[\text{scope}]{\text{Increase in}}$ hundreds/thousands of neurons in a neural network
- Action potential $\xrightarrow[\text{accuracy}]{\text{Decrease in}}$ binary spike events or firing rate
- Synapses $\xrightarrow[\text{complexity}]{\text{Shift in}}$ weight of synapse



Data Analysis/Statistical Models

- Needed because data is *noisy.* Repeated experiments, however well-controlled, will yield different results.
- Statistical models describe data in terms of probability distributions
- Statistical modeling is an iterative process that begins with exploratory analysis and ends (perhaps) with assessment of fit.
- **"All models are wrong, but some are useful"**



Outline of Possible Research Projects

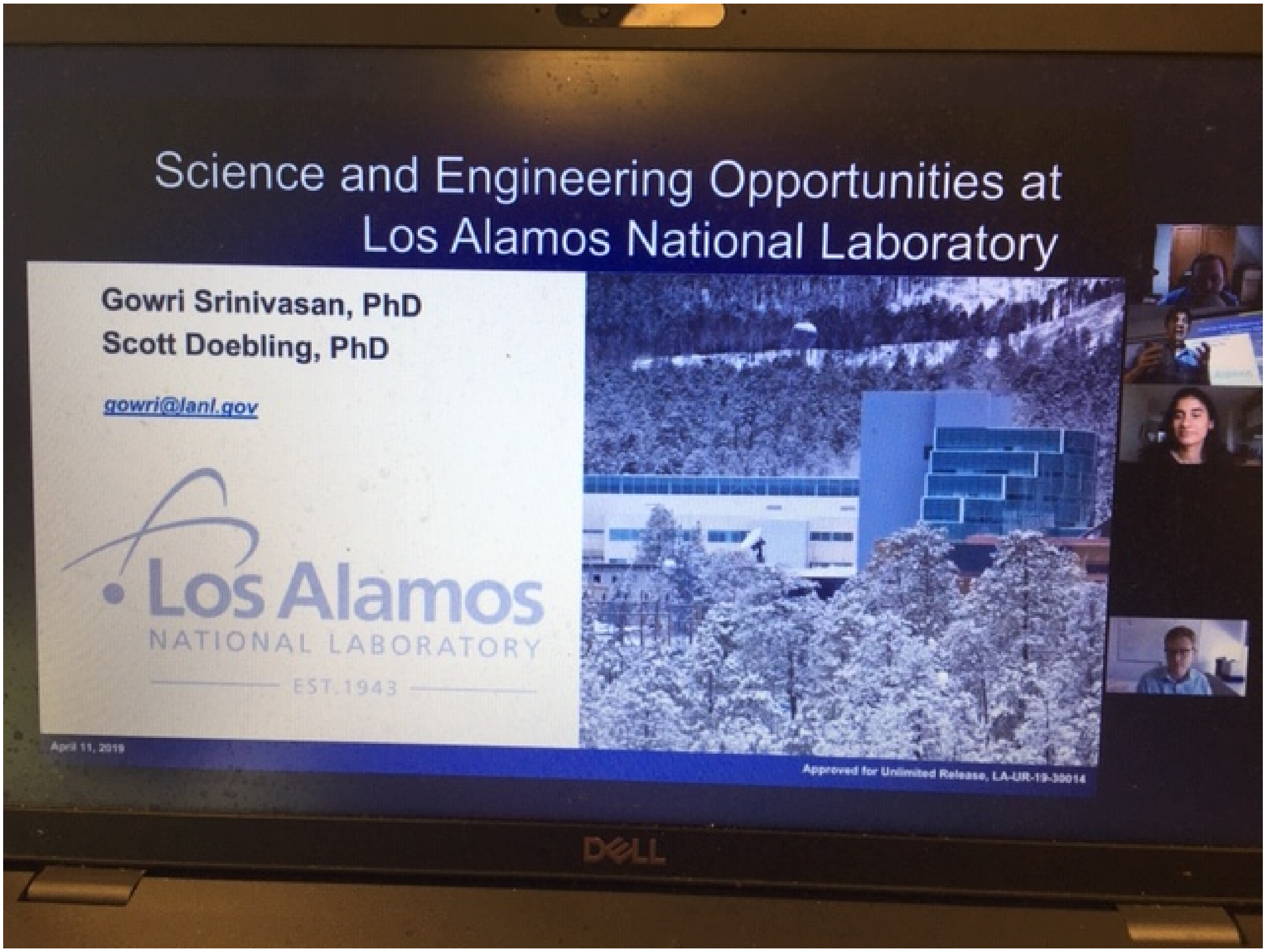
Purpose: Better understand sequences of place cell activity in the brain.

Modeling: How can changes in the synaptic weights lead to these sequences?
- We'll build on work done by Sabrina Hetzel, SMU grad student, as well two published modeling studies.
- The project involves adapting provided Matlab code to test hypotheses.

Data Analysis: Can we use a particular algorithm to find these sequences in simulated data and real data?
- We'll build on the work done by Duc Truong, former SMU grad student, in finding sequences in hippocampal data.
- The project involves adapting the algorithm given that place cells encode space.
- We'll start with simulated data in which we know what to expect, and then analyze data from Brad Pfeiffer's lab recorded as the rat explored a 1D track.

Basic Timeline:
- Week 1: Tutorials preparing you for both
- Friday, 6/25: Divide into two groups and make a project proposal
- Week 2: Work within groups with daily help from TA's and ,meetings with advisors
- Friday, 7/2: Presentations in the morning
  - Published research paper you selected to study during Week 2
  - Research results and possible future directions

III. Sample other activities: Presentation of Internship opportunities at the Los Alamos National Laboratory



IV. Sample of student’s presentation (Aurod Ounsinegad, Humberto Gutierrez)

REU 2 – Kuramoto Model with Forced Sinusoidal Coupling Project Report

Throughout the duration of the first week of this REU we were taught about the Yoshiki Kuramoto Model and how it relates and speaks about the concept of coupled and infinite oscillators. Along with this we were taught about the intricacies of the wave and heat equations and how to implement those very same intricacies into MATLAB code in order to get the full scope of how the heat and wave equations work in our day to day lives. As you can tell the first week of the SMU REU, Dynamics in Complex Systems, was very lecture heavy; however, the countless hours of lecture within the first week of the REU were what led us students into our topic choices for the research portion of the REU.

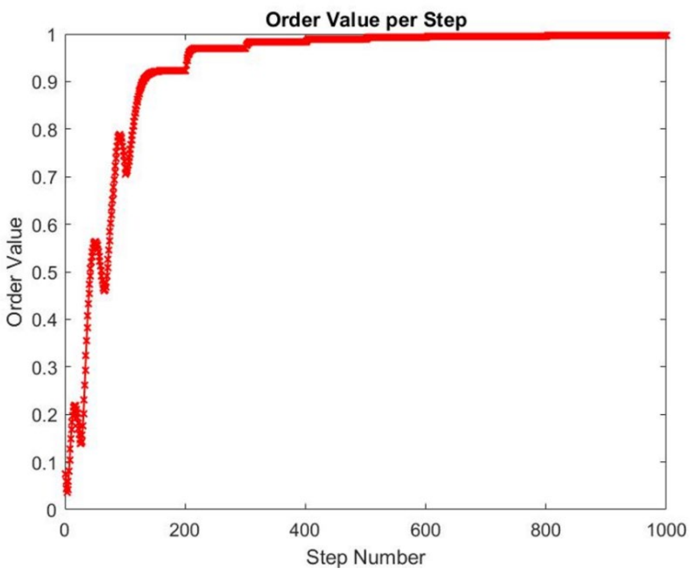
This brings me to the second week of the REU, this is where us students chose our research topics and worked throughout the week to refine our results enough to give a 30-minute presentation by the end of the week. The research topic that my group ended up choosing to work on for the duration of the second week of the REU has to do with forced sinusoidal coupling within the Kuramoto model. Our choice of this topic was influenced by Childs and Strogatz 2008 paper, Stability diagram for the forced Kuramoto model, where they summarized and dived deep into the inner workings of the Kuramoto forced model. When looking into this article we decided that it would be interesting to look into how the forced external drive affected the sinusoidal coupling of the system of oscillators.

When approaching this topic, we decided it would be best if we first looked over the Childs and Strogatz 2008 paper to determine which equations needed to be used as well as understand how those equations were found and/or derived. The equation that we used, and the equations that led up to its formation were:

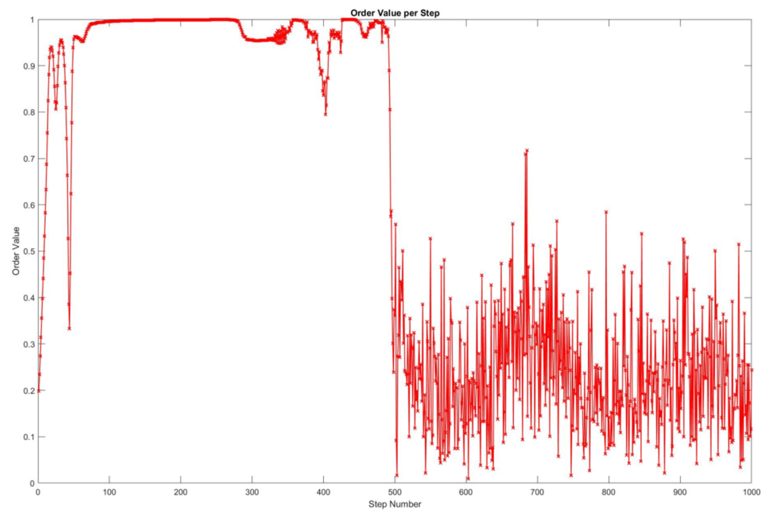
$$\frac{d\vartheta_i}{dt} = \omega_i + \frac{K}{N}\sum_{j=1}^{N} sin\left(\vartheta_j - \vartheta_i\right) + F\, sin\, (\sigma t - \vartheta_i)$$
$$\theta_i = \vartheta_i - \sigma t$$
$$\frac{d\theta_i}{dt} = (\omega_i - \sigma) + \frac{K}{N}\sum_{j=1}^{N} sin\left(\theta_j - \theta_i\right) - F\, sin\, (\theta_i)$$

Once we decided on the equations that we were going to use, we were given permission by Dr. Ross Parker to use the MATLAB Script that he had created towards our research topic. From here we began modifying the equations within the code so we could play around with the new parameters that we created in order to see how the system would react. This is where we would begin our week-long journey to refine the results tour model would give us.

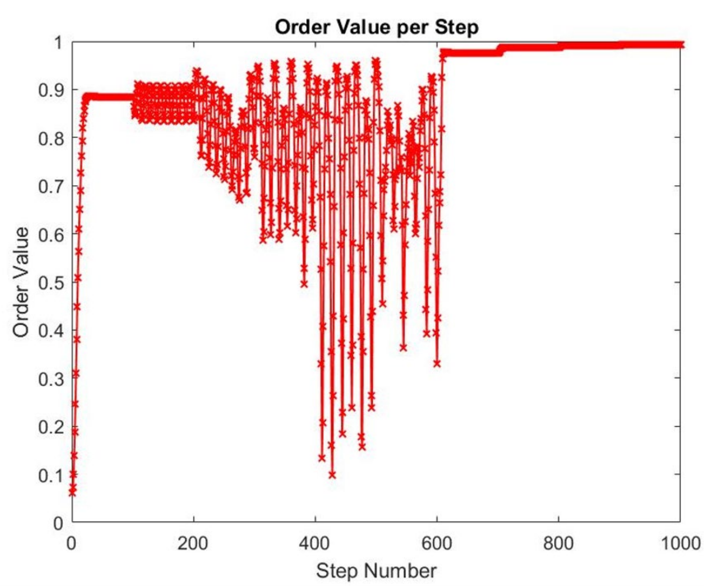
After playing around and refining our parameters we began getting results that we expected to see when we started our research at the start of the week. We created a graph that would show us the order of the oscillators, a value between 0 and 1, at each step within the system. This graph, along with the force vector we created that would gradually change force in the system, gave us the simulations that we were looking for at the start of the week. We were aiming to see what the parameter values were at when synchrony was met within the simulations as seen in this report.



However, synchrony was not always met, some simulations that were obtained gave temporary synchrony, others never reached synchrony but always came very close. Although this is the case, we noticed a lot of correlations with the simulations that we obtained. We realized the clear ratio between the coupling parameter (K) and force strength (E) and how if K were increased high enough the ratio was thrown out as the value for K would overpower the system into synchrony. It was also found that when the value of the force strength was increased to 5 or 6, as seen in the simulations above and below, the order would either reach synchrony or drop out of a state of synchrony into a state of desynchrony.



As the week comes to an end, we believe that we have accomplished what we had hoped for and even more, although there were many ups and down this past week, we are proud of the results we obtained. However, we realize that with more time, our results could most definitely be refined, errors resolved, and new ideas can be formed. In specific, we found numerical error within our model having to do with our step size on the day before we gave our presentation; therefore, we had little to no time to correct this numerical error. But with more time we believe we could delve deeper into the roots of this numerical error and fix it, with this



error fixed and patched we believe that we could look further into varying parameters such as our strength frequency in the same way we varied our force strength. All in all, we are proud of the results that we got from our model and hope that in the future we can refine our results and numerical errors so we can obtain more information on the dynamics of synchrony within our system!