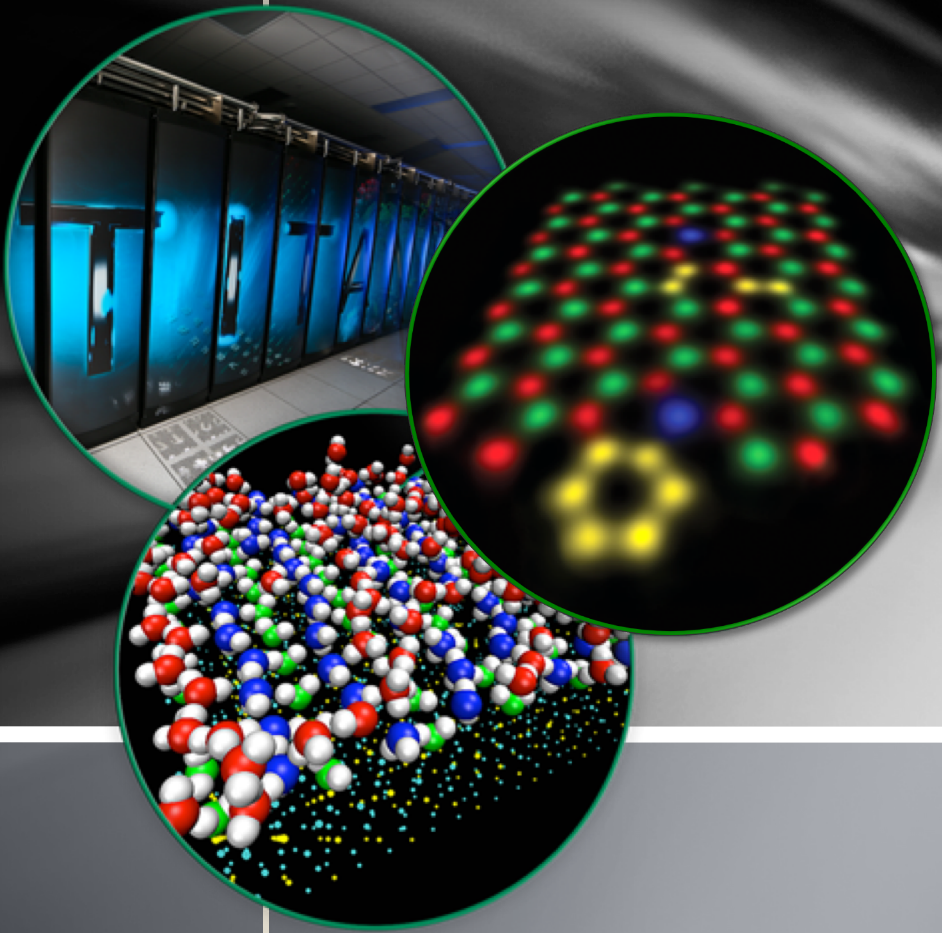
Two-terminal, soft, biomembrane-based devices that can sense, process, and learn



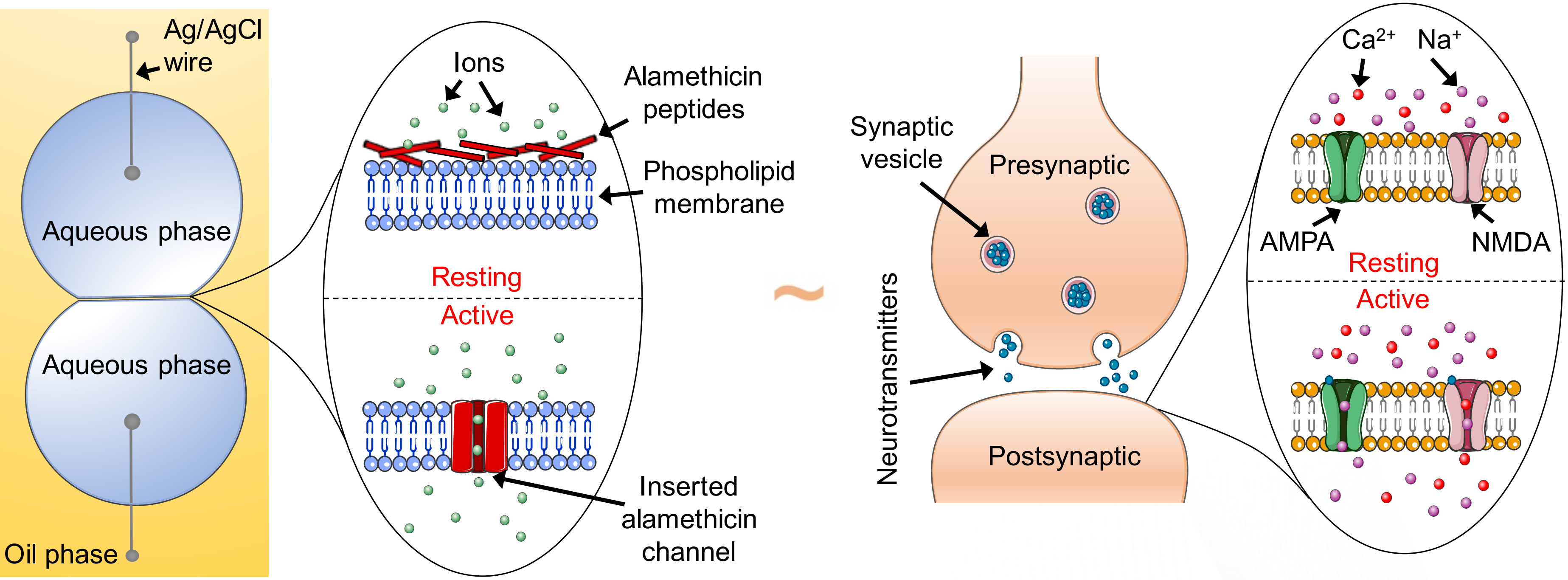
Joseph Najem
Andy Sarles
Pat Collier
Alex Belianinov
Katie Schuman

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Concept for a two-terminal biomolecular synaptic mimics

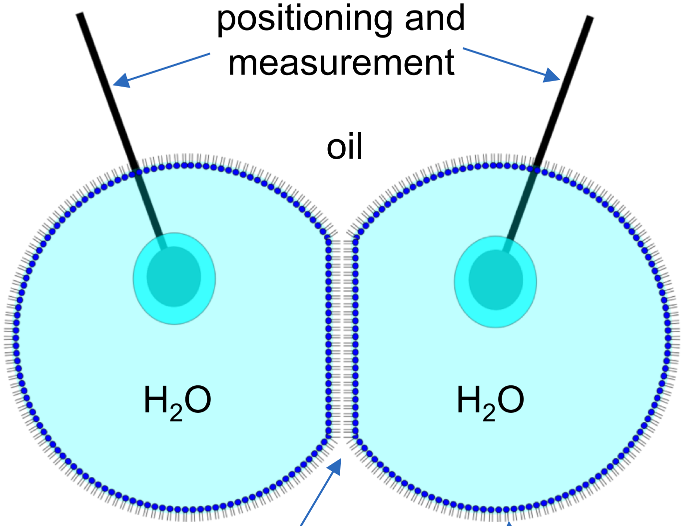
A two-terminal, biomolecular memristor featuring similar structure (biomembrane), switching mechanism (ion channels), and ionic transport modality as biological synapses while operating at considerably lower power.



- Biological synapses enable electrochemical transport of information. Key processes are voltage and ion-selective transport via transmembrane channels.
- The behaviors of synthetic memristors are largely phenomenological; they are also noisy and power-hungry!

Najem, J. S.; et al. *ACS Nano* **2018.**

Droplet Interface Bilayers: insulating model membranes



Electrodes for positioning and measurement

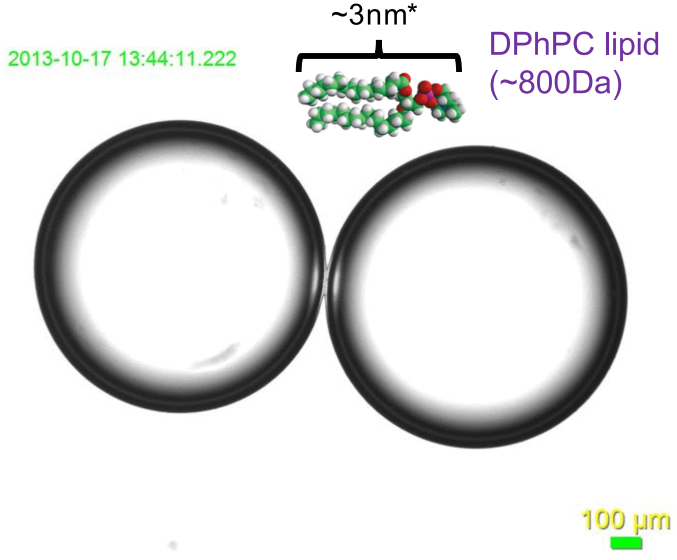
oil

H_2O

H_2O

5nm-thick lipid bilayer membrane

surfactant monolayer-coated droplets

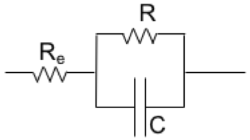


DPhPC lipid (~800Da)

Funakoshi, K., H. Suzuki, and S. Takeuchi, Anal. Chem., 2006. 78(24): p. 8169-8174.
Holden, M.A., et al., J. Am. Chem. Soc., 2007. 129(27): p. 8650-8655.
Hwang, W.L., et al., J. Am. Chem. Soc., 2008. 130(18): p. 5878-5879.
Poulin, P.; Bibette, J., Langmuir 1998, 14 (22), 6341-6343.

Building blocks for cell-inspired compartmentalized materials…

Equivalent circuit

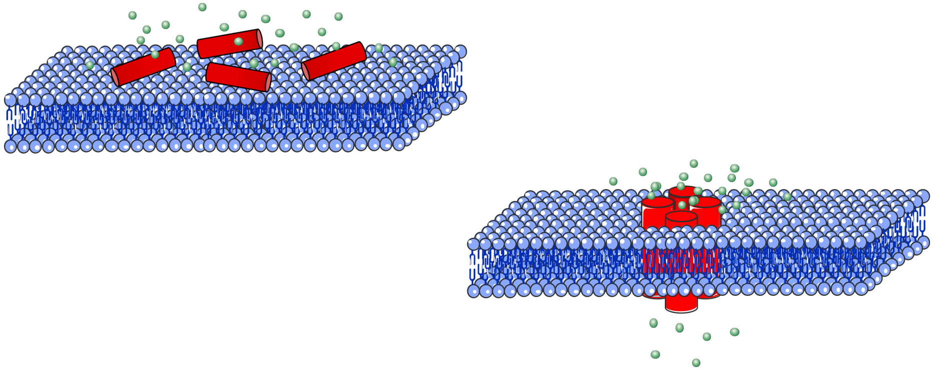


R_m ~ 10-100 MΩcm^2
C_m ~ 0.6 µF/cm^2

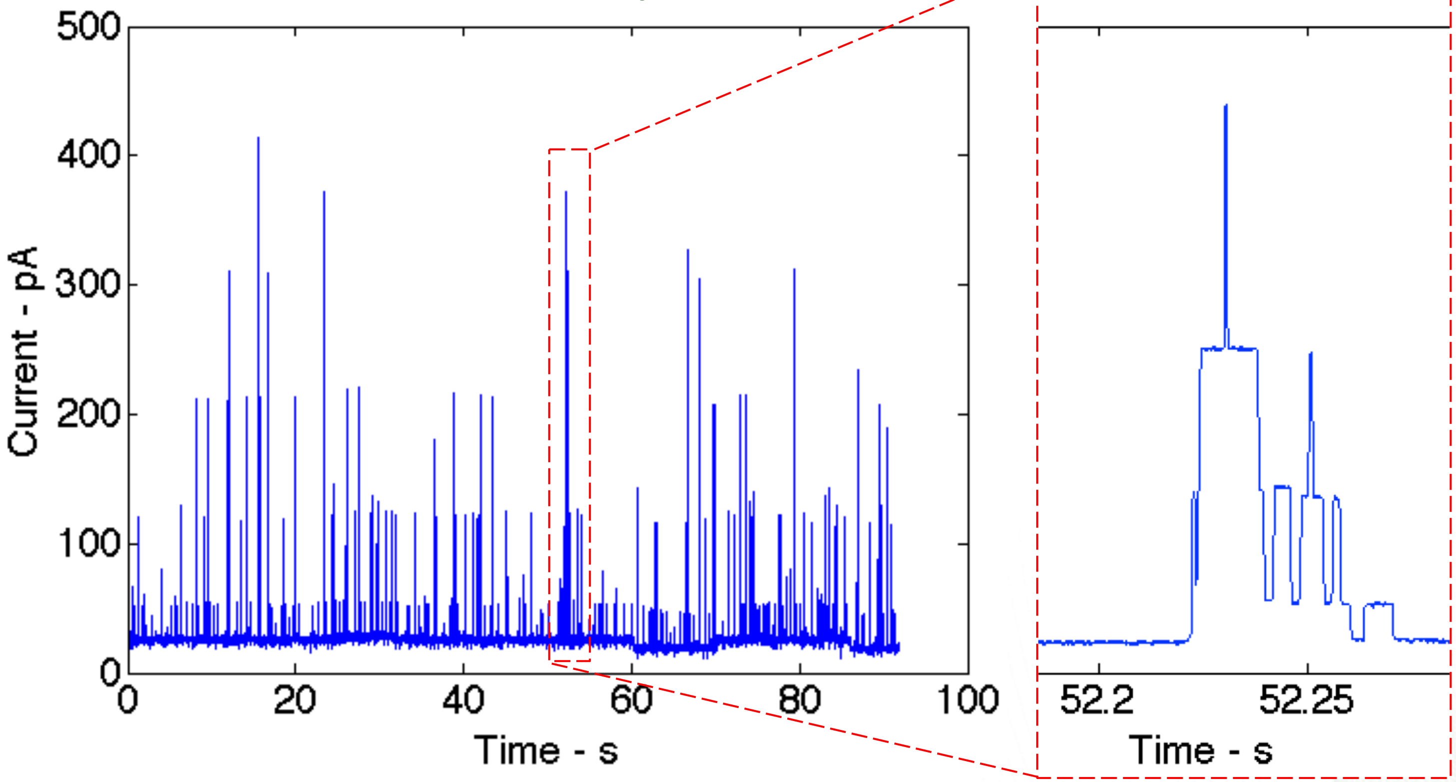
$$R_m \equiv R \times A$$

$$C_m \equiv \frac{C}{A} = \frac{\varepsilon}{d}$$

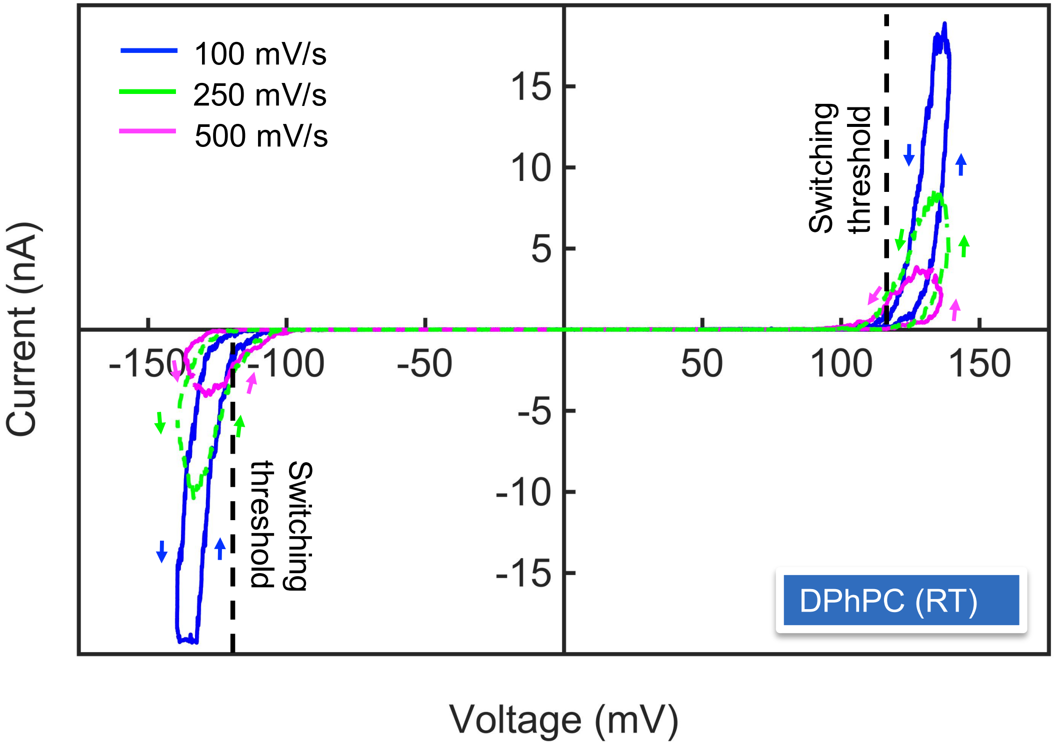
Alamethicin peptides form voltage-dependent ion channels

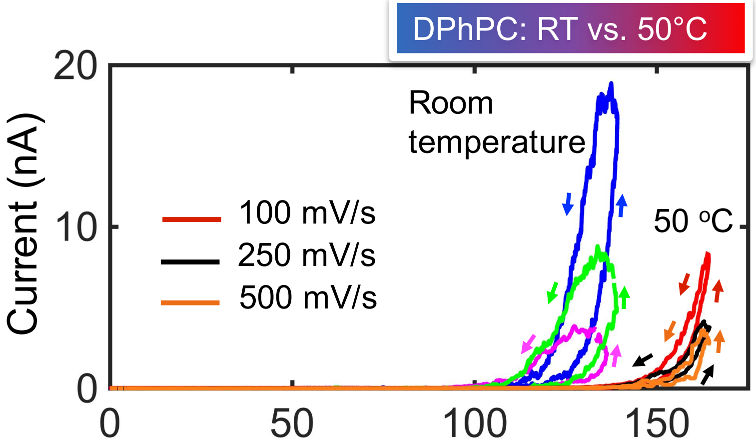


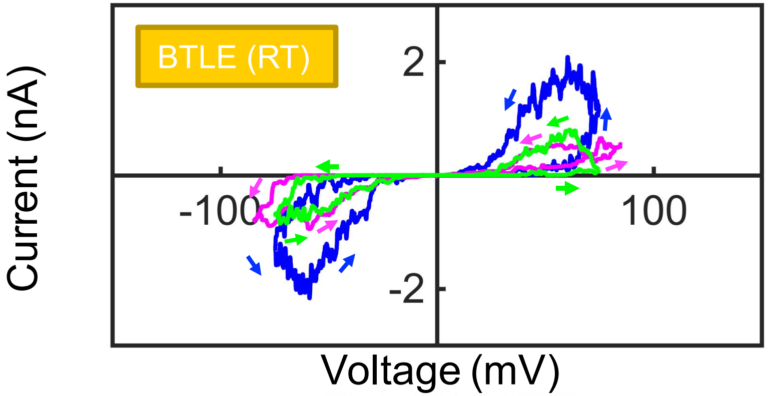
Conductive pathways are created in the insulating membrane in response to voltage

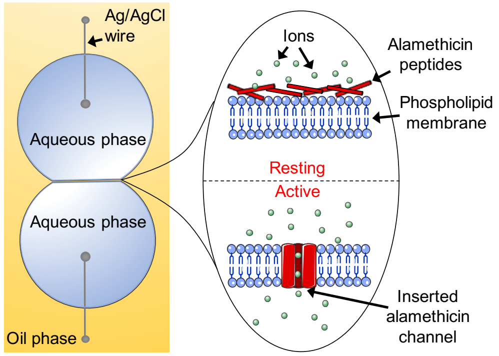


Current-voltage relationships of alm-doped biomembranes







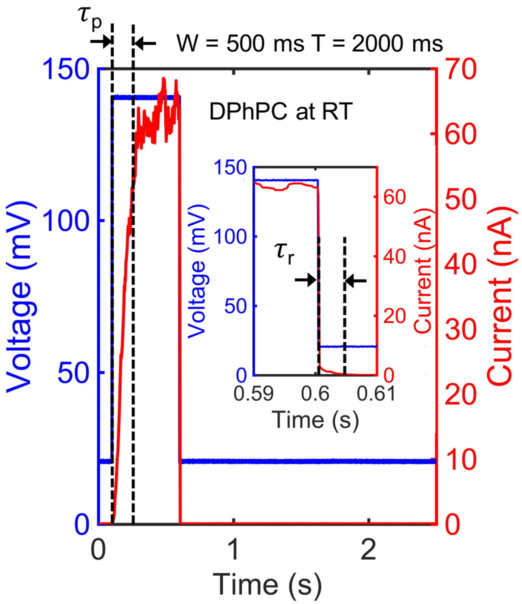


> “…a memristor is best defined as any two-terminal device that exhibits a *pinched hysteresis loop* in the voltage–current plane when driven by *any* periodic voltage…”

Chua, L., *Semiconductor Science and Technology* **2014,** *29* (10), 104001.

Najem, J. S.; et al. *ACS Nano* **2018**.

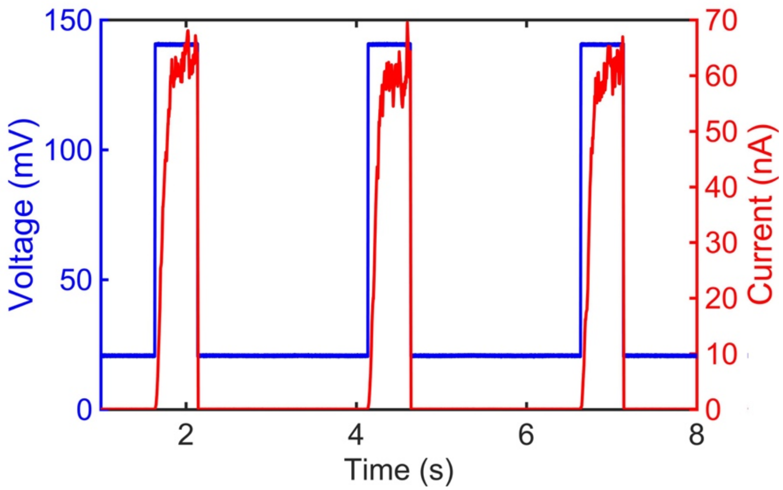
Dynamic switching performance and switching longevity

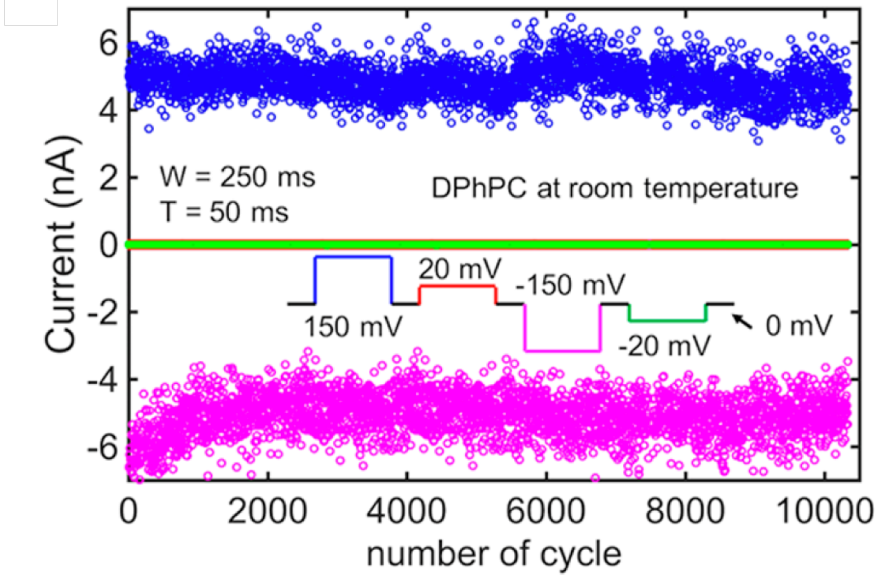


Lipid type	Temperature	$V_{threshold}$ (mV)	τ_r (ms)	τ_p (ms)	τ_d (ms)
DPhPC	RT	120	6.8 ±1.2	99.5 ±17.7	1 ±1.3
DPhPC	50 °C	150	3.7 ±0.5	75.1 ±11.1	8.55 ±2.74
BTLE	RT	25	100 ±37	420 ±61.2	23.3 ±6.11

NMDA relaxation ~ 100's of ms

Lester, R. A. J., et al., *Nature* **1990,** *346*, 565.





Najem, J. S.; et al. *ACS Nano* **2018**.

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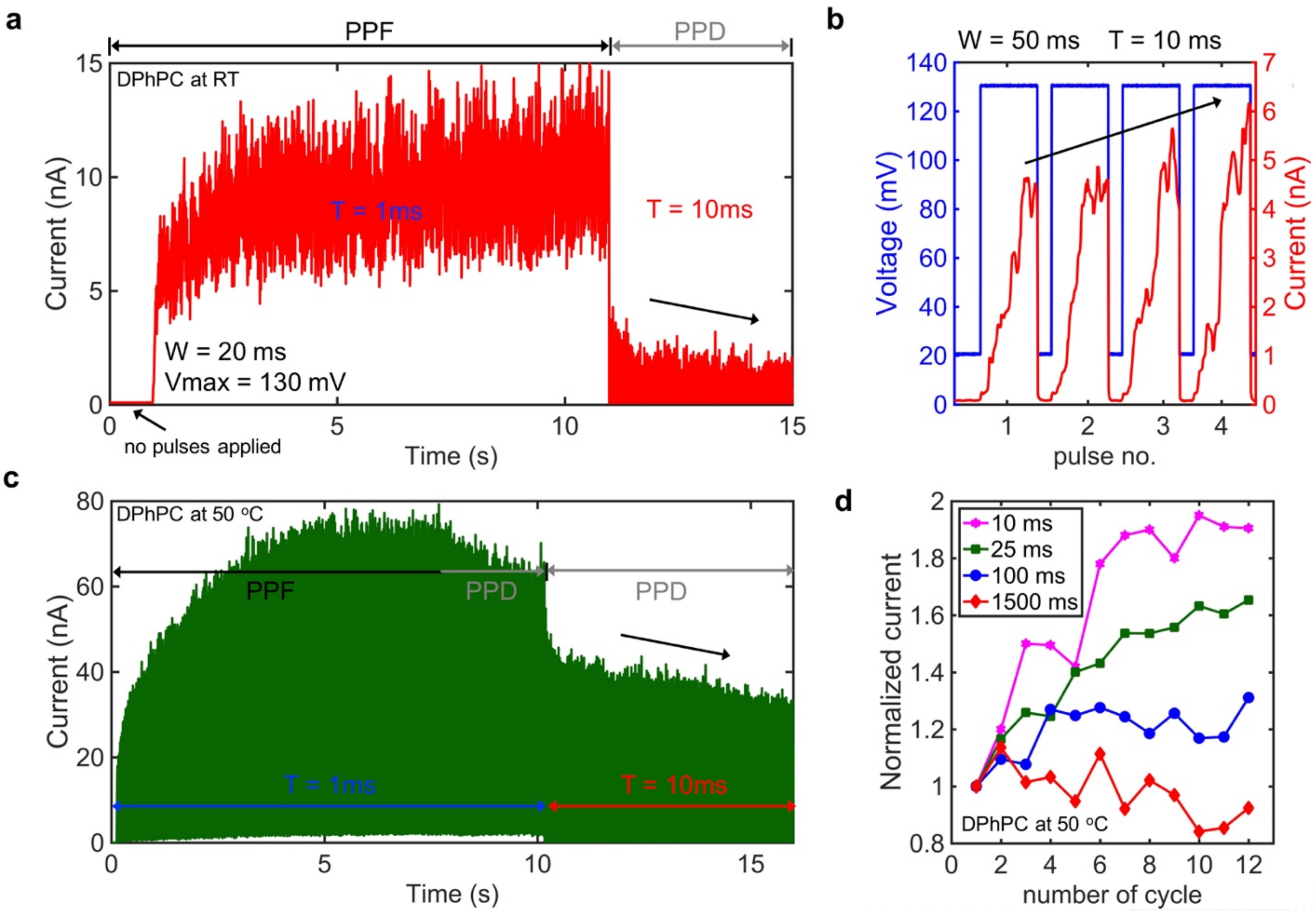
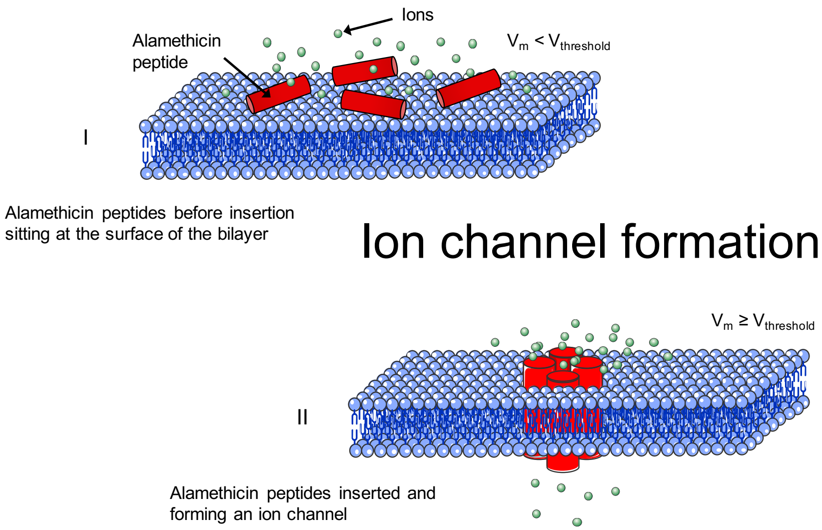
Short-term learning across multiple voltage pulses (PPF & PPD)



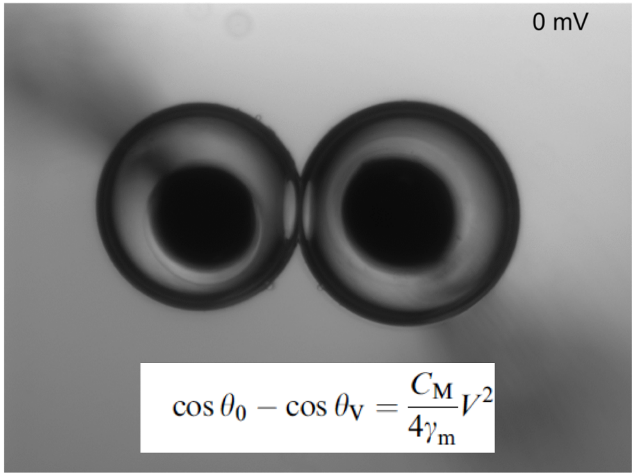
Najem, J. S.; et al. *ACS Nano* **2018**.

So, what “states” are dictating these responses?

Ion channel formation



Electrowetting



$$\cos\theta_0 - \cos\theta_V = \frac{C_M}{4\gamma_m}V^2$$

$$I = G(N_a, A_m)V$$

N_a = number of alm pores per m^2
A_m = fractional change in area due to EW

$$\frac{dN_a}{dt} = \frac{1}{\tau_0 e^{V/V_\tau}}\left(N_0 e^{V/V_e} - N_a\right)$$

Dynamics of alamethicin gating

Okazaki, T., et al., Biophysical Journal 2003, 85 (1), 267-273.

$$\frac{dA_m}{dt} = \frac{1}{\tau_{ew}}\left(\alpha v^2 - A_m(t)\right)$$

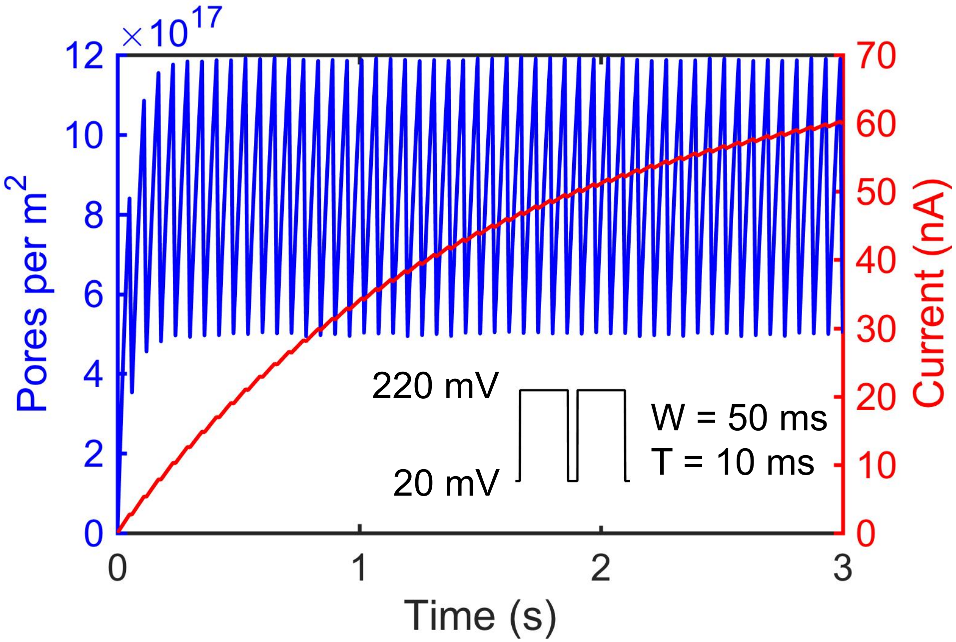
Dynamics of electrowetting

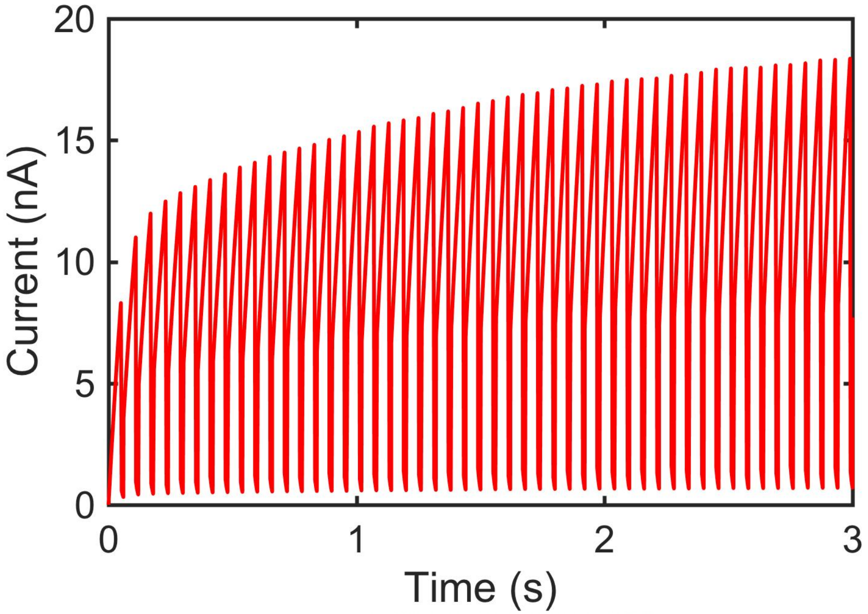
$$G(V,t) = G_u N_a(V,t) A_0 \left(1 + A_m(t)\right)$$

Reciprocal of memristance

Najem, J. S.; et al. *ACS Nano* **2018**.

Simulations of short-term plasticity in a biomolecular memristor

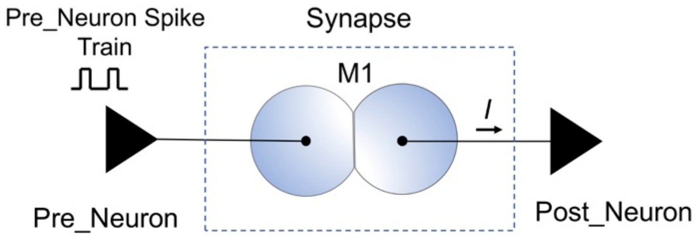


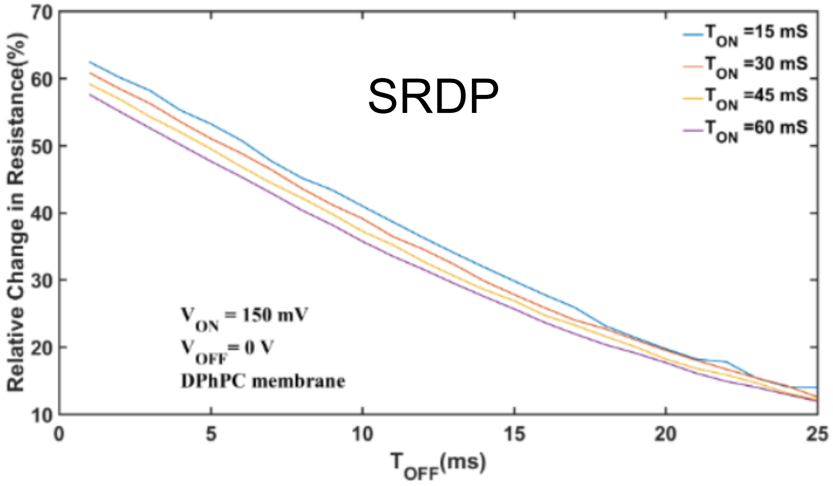


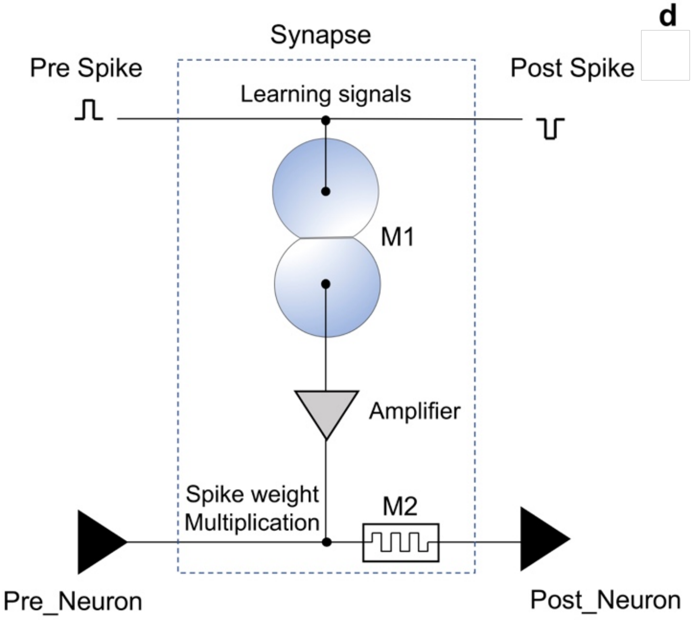
Slow formation of new bilayer area and fast insertion of new channels leads to PPF-like short-term learning responses!

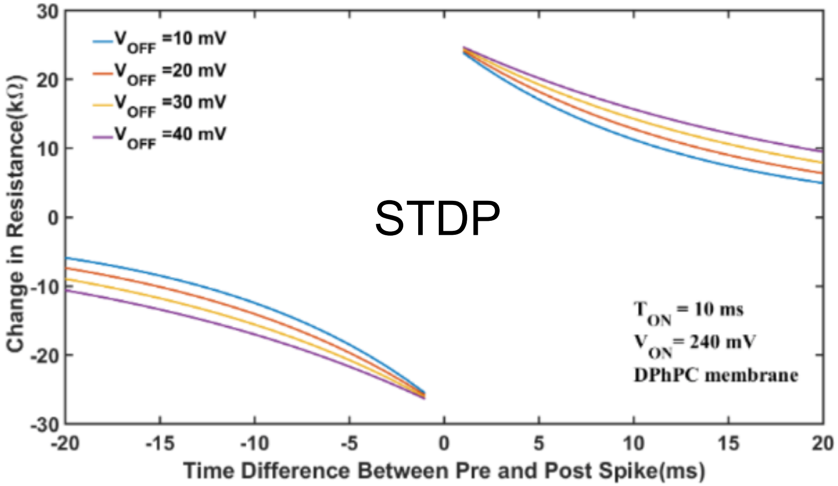
Najem, J. S.; et al. *ACS Nano* **2018**.

Online learning circuit application: Short- and Long-term learning







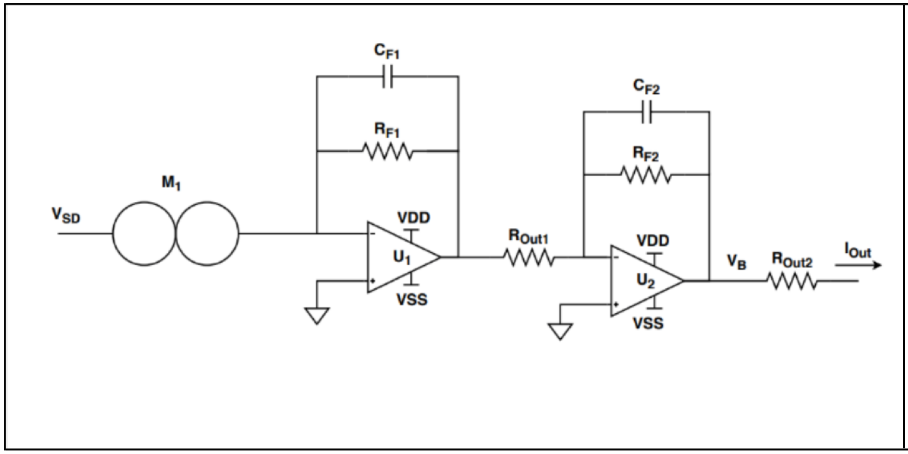


Sakib Hasan, Ryan Weiss, and Garrett Rose

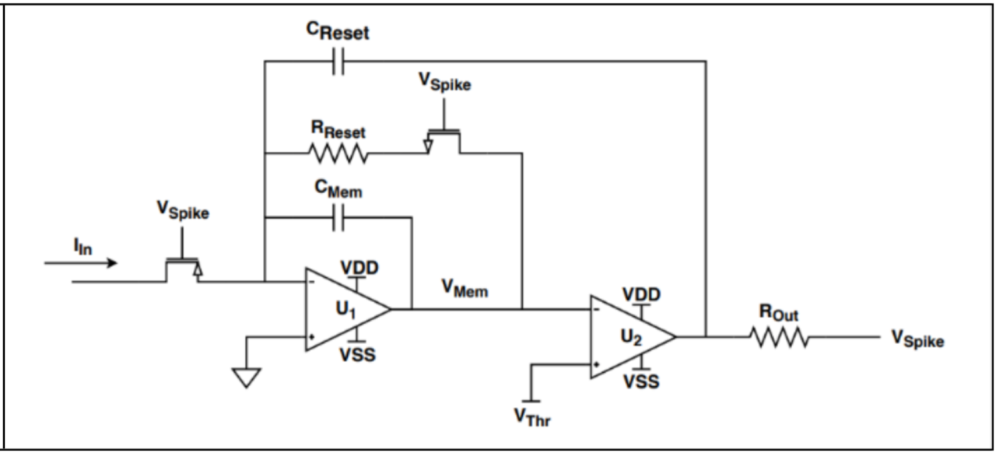
Unpublished data (submitted)

Experimental demonstration of short-term learning

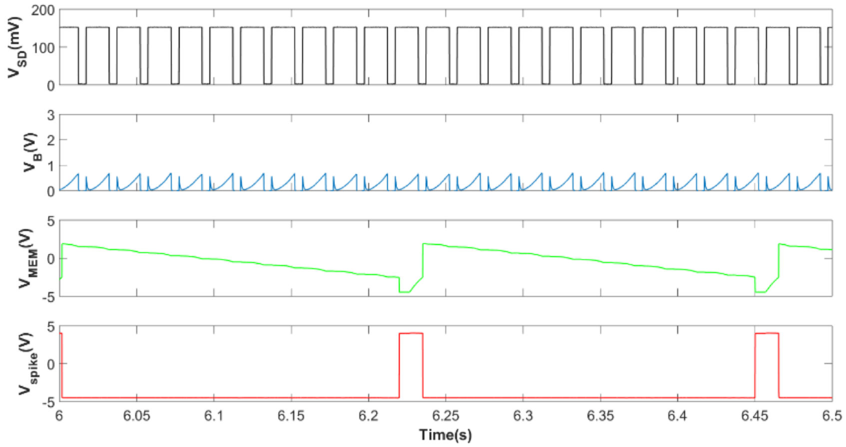
Synapse



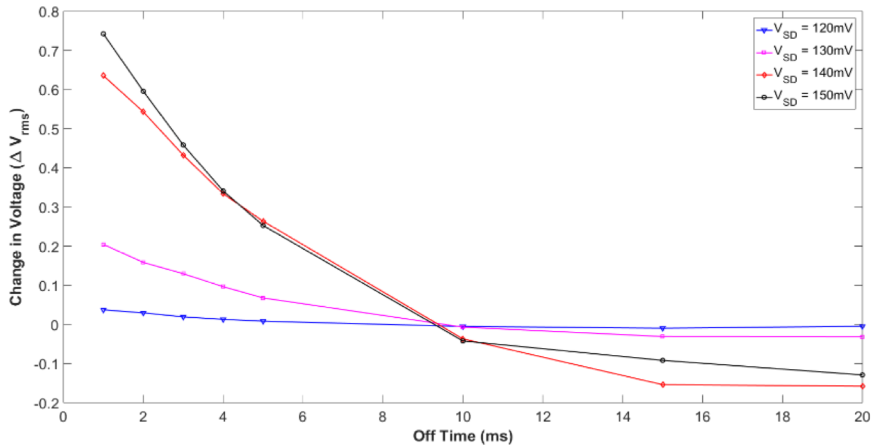
Neuron



Spike trains test voltages for 5ms off time



Spike-rate-dependent Plasticity



TENN LAB
NEUROMORPHIC
ARCHITECTURES. LEARNING. APPLICATIONS.

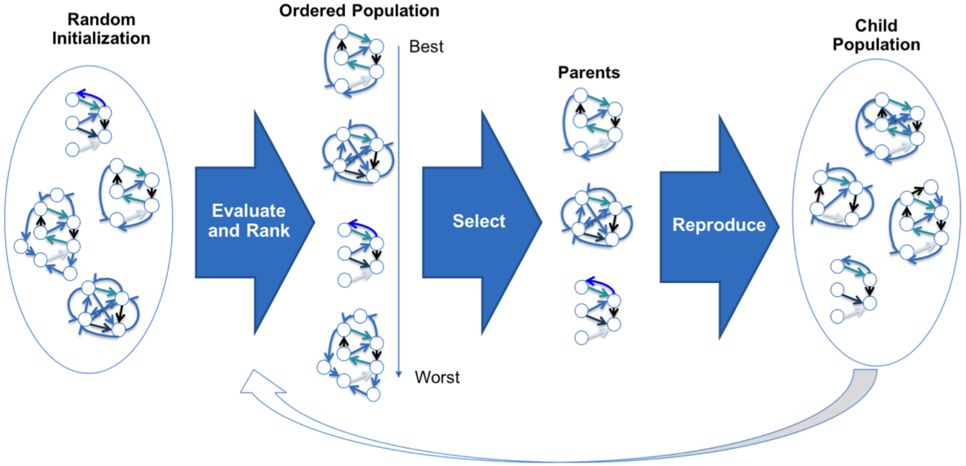
Ryan Weiss, Sakib Hasan, and Garrett Rose

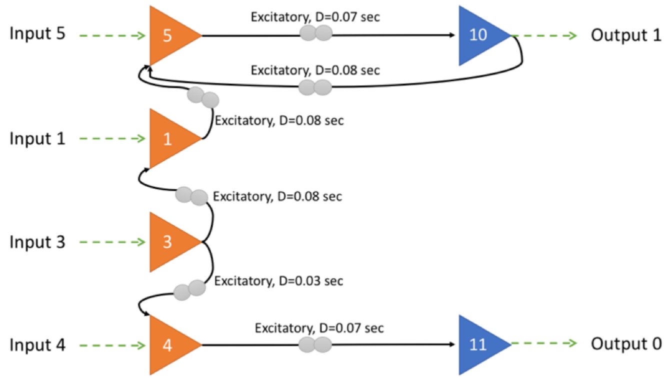
Unpublished data (submitted)

OAK RIDGE
National Laboratory

How do we train DIB-based neuromorphic systems?

Evolutionary Optimization for Neuromorphic Systems (EONS)





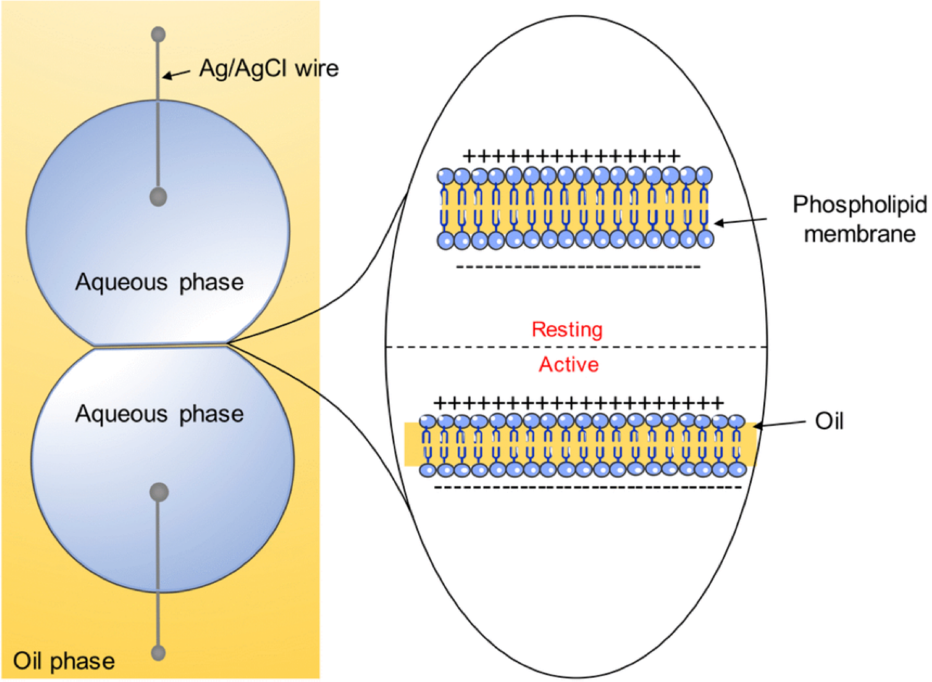
Network for EEG classification task:
Training Accuracy: 98.5%
Testing Accuracy: 98.5%
6 neurons, 6 synapses

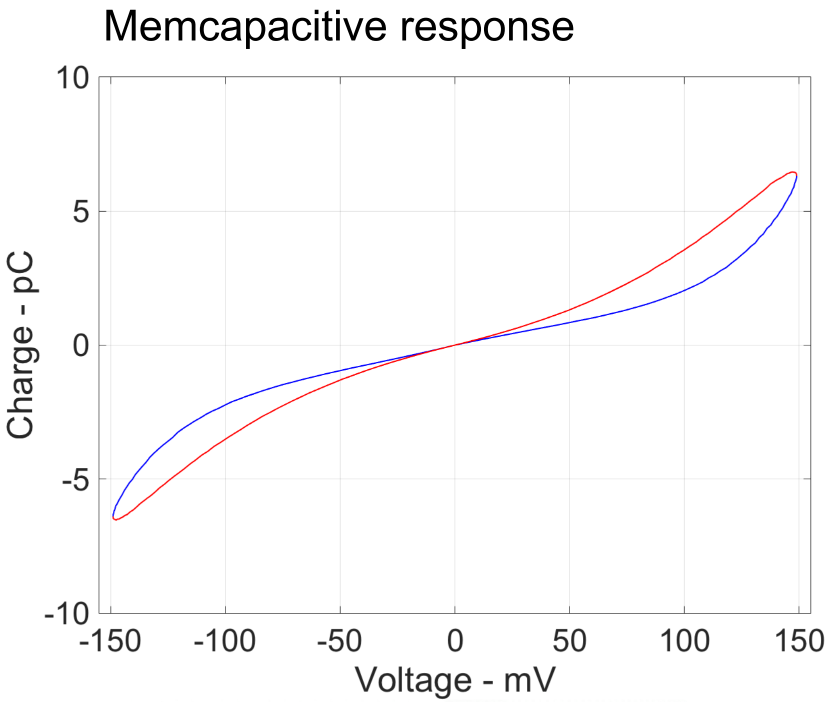
Catherine Schuman, and Nick Skuda

Unpublished data (submitted)

Reconfigurable soft-matter interfaces exhibit memory capacitance too!

The same setup void of any memristive ion channels exhibits a memcapacitive behavior. Memcapacitors have been theorized but never realized.

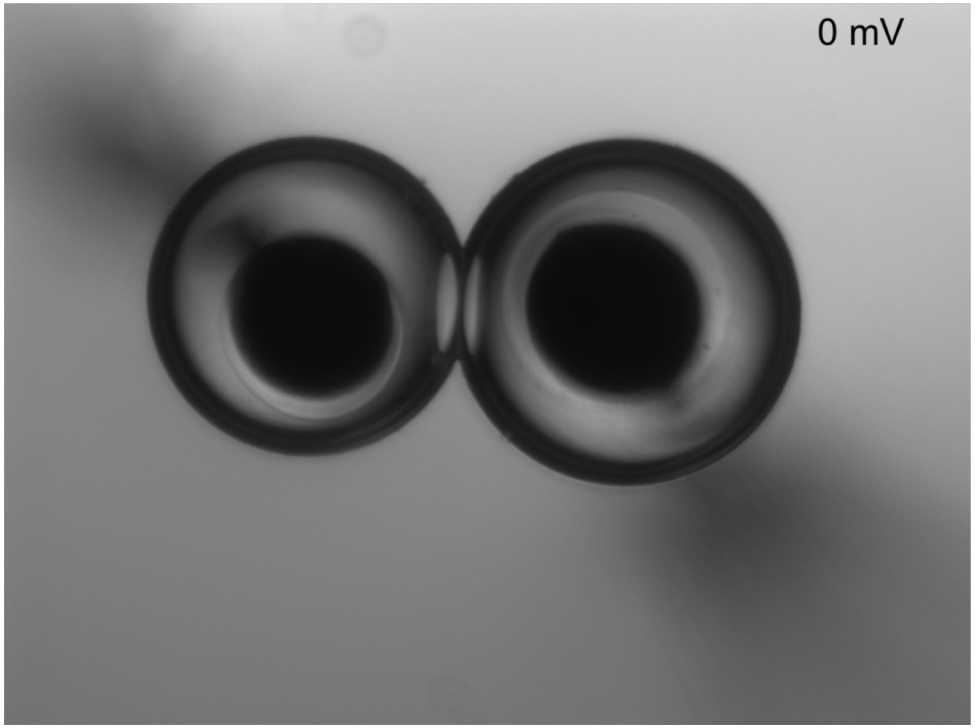




Unpublished data (in prep)

The geometry of the bilayer interface changes in response to voltage

The same setup void of any memristive ion channels exhibits a memcapacitive behavior. Memcapacitors have been theorized but never realized.



Upon application of a transmembrane voltage bias *v* (DC or AC) two phenomena occur:

1) **Electrowetting** which results in an increase in membrane area (i.e. radius ***r***) driven by changes in surface tension.
2) **Electrocompression** which results in a decrease in membrane thickness (***w***) driven by compressive forces generated by the attraction between opposite charges.

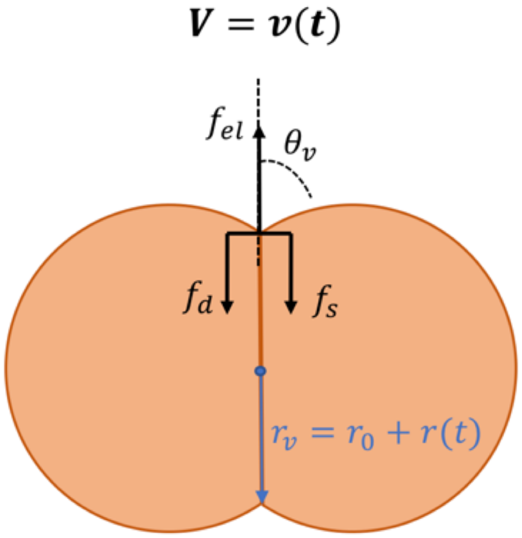
Unpublished data (in prep)

State variable and equations

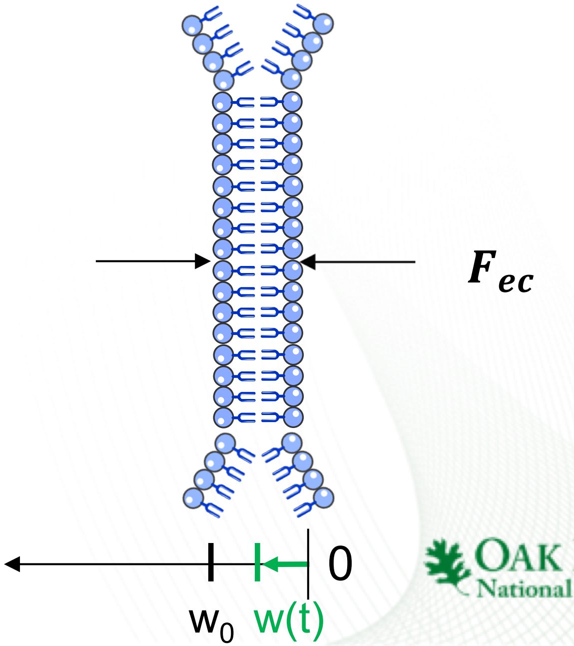
$$\boxed{q = C(r,w)v}$$

$$\boxed{\xi_{ew}\frac{dr(t)}{dt} + k_{ew}r(t) = f_{el}(t)}$$

$$\boxed{\xi_{ec}\frac{dw(t)}{dt} + k_{ec}w(t) = F_{ec}(t)}$$



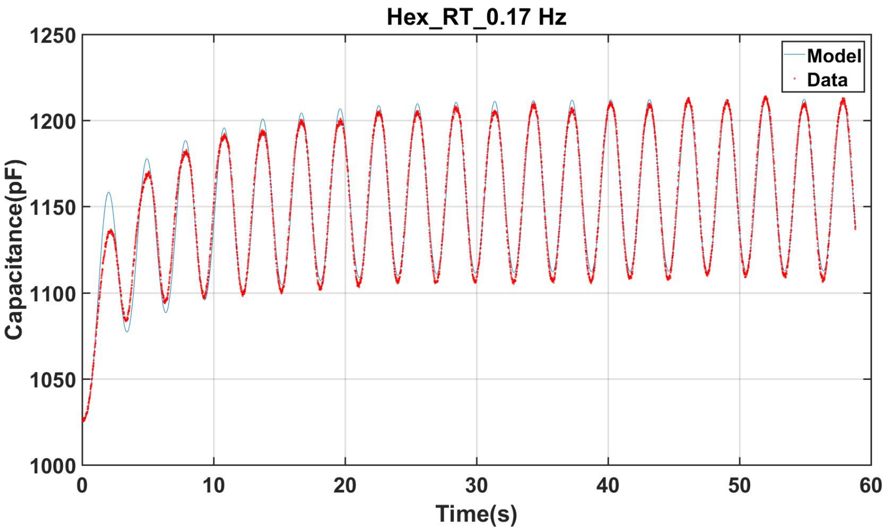
$$f_{el} = f_d + f_s$$

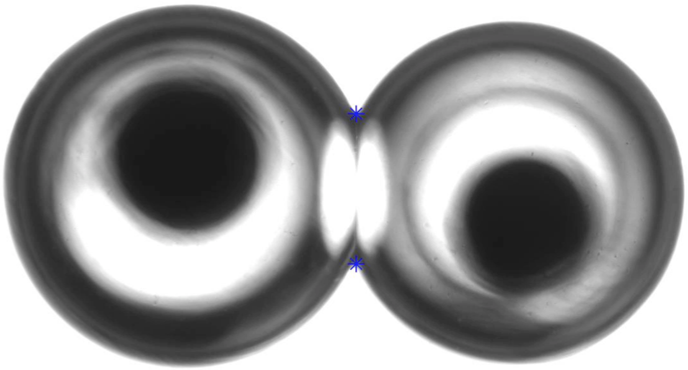


Unpublished data (in prep)

State variable and equations

Hexadecane
Sinusoidal (150 mV, 0.17Hz)





Electrowetting

$$\frac{dR_1}{dt} = R_2$$

$$\frac{dR_2}{dt} = \frac{-{R_2}^2}{R_1} + \frac{k_{ew} r_0 R_2}{\xi_{ew} R_1} - \frac{2k_{ew} R_2}{\xi_{ew}} + \frac{\varepsilon\varepsilon_0 v^2 R_2}{\xi_{ew} R_1 W_1} - \frac{\varepsilon\varepsilon_0 v^2 W_2}{\xi_{ew} {W_1}^2} + \frac{\varepsilon\varepsilon_0 v \dot{v}}{\xi_{ew} W_1}$$

Electrocompression

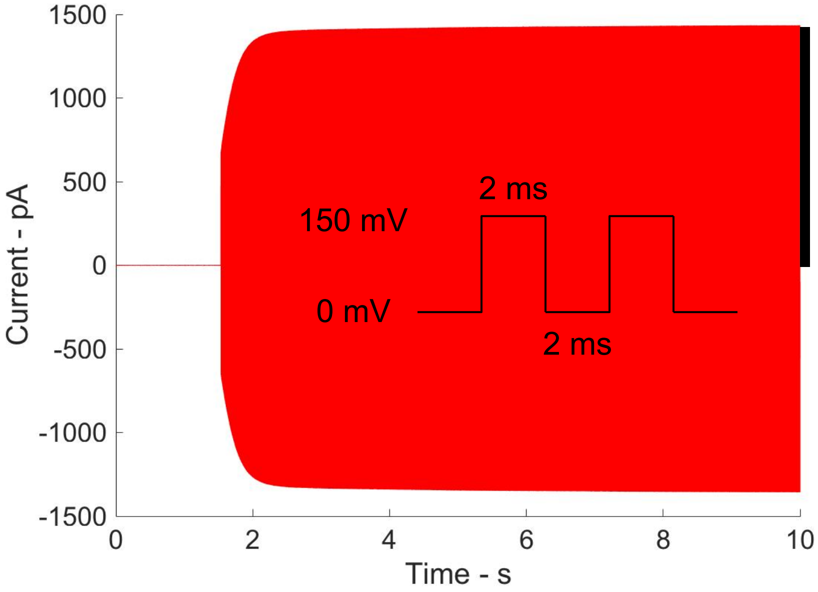
$$\frac{dW_1}{dt} = W_2$$

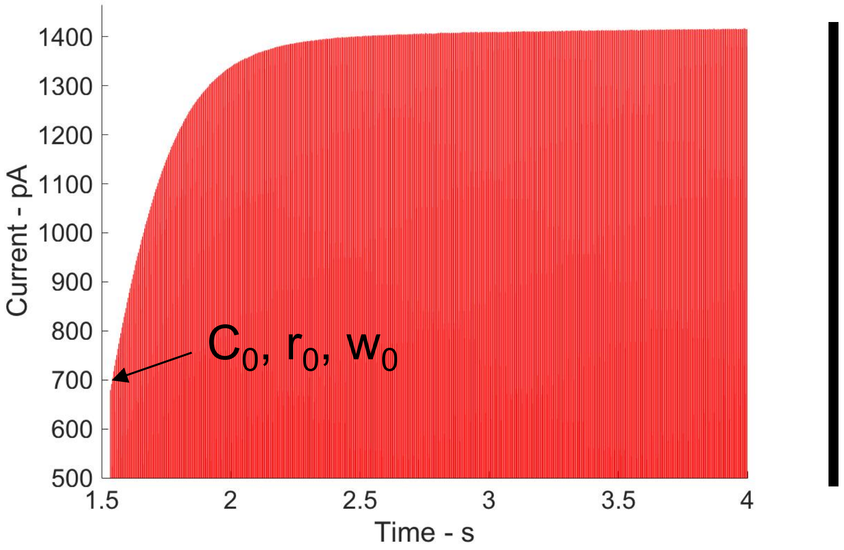
$$\frac{dW_2}{dt} = \frac{-W_2\left(k_{ec}{W_1}^3 + \beta v^2 {R_1}^2\right)}{\xi_{ec}{W_1}^3} + \frac{\beta v\left(v R_1 R_2 + 0.5{R_1}^2 \dot{v}\right)}{\xi_{ec}{W_1}^2}$$

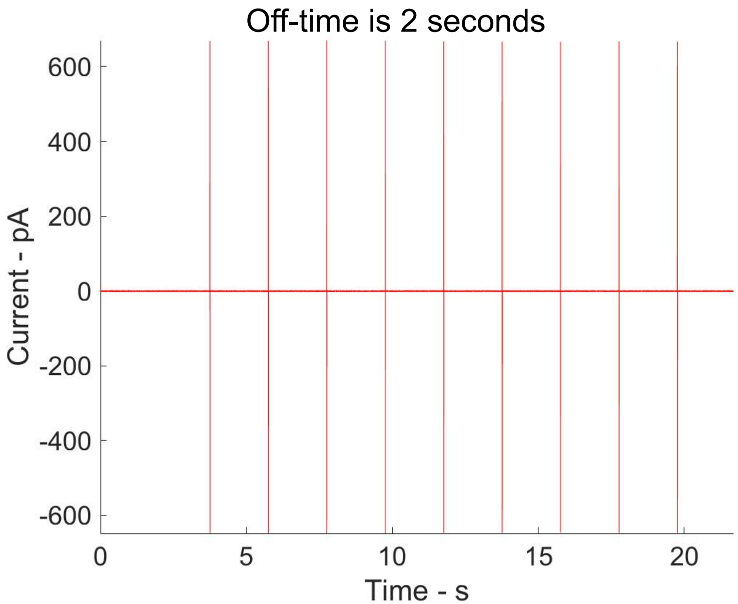
- The units for ξ_{ew}, k_{ew} are (**N.s/m²**) and (**N/m²**), respectively
- The units for ξ_{ec} and k_{ec} are (**N.s/m**) and (**N/m**), respectively

Unpublished data (in prep)

Plasticity and signal processing







There are two time constants, one related to EC (the quick rise) and the other related to EW (the slow rise)…

Unpublished data (in prep)

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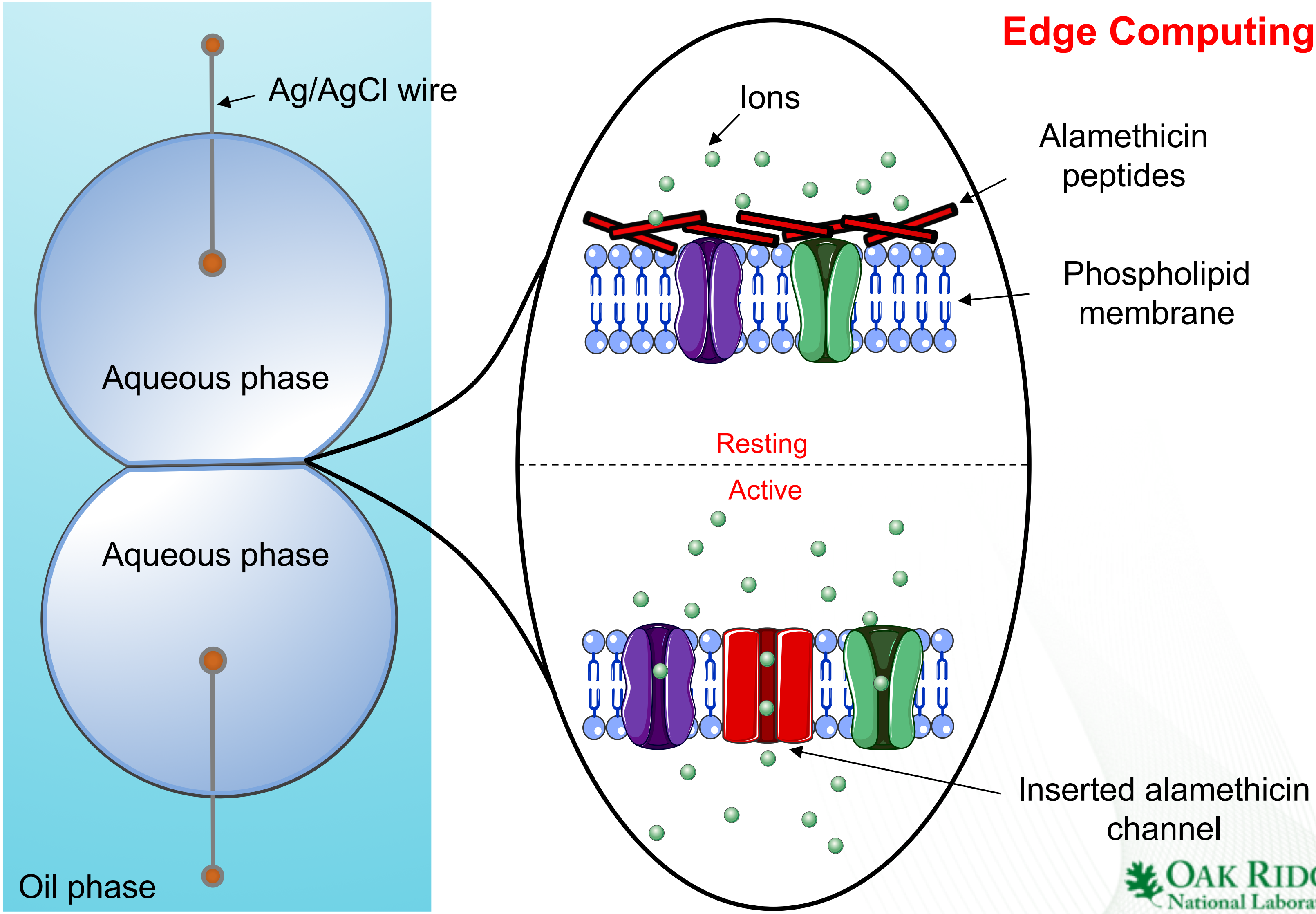
Our system is great for sensing and signal processing applications

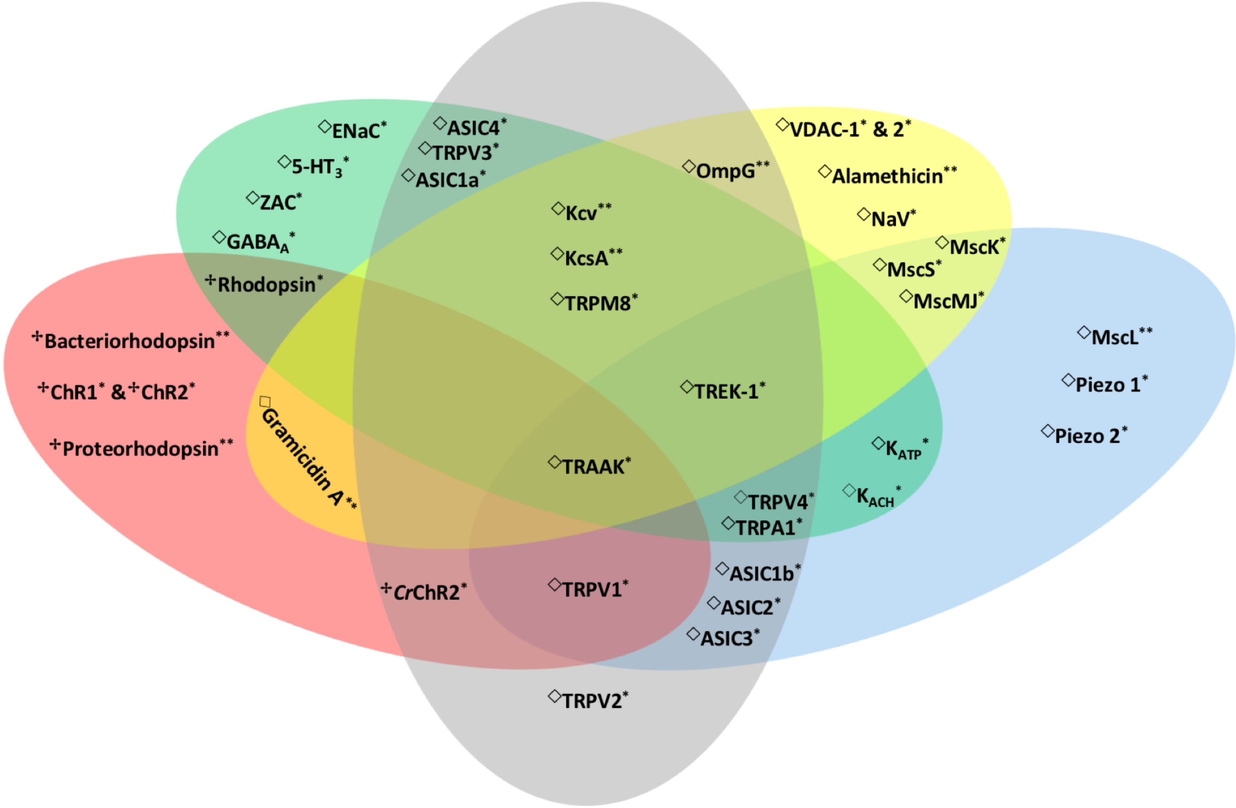
We are not limited to a single type of ion channels. Multiple stimuli-responsive ion channels could be used for applications in sensing and signal processing.



Edge Computing?!

A wide variety of ion channels and pumps could be investigated

*Reconstituted **Reconstituted in DIBs ◇ Ion channel ✢ Ion pump



🟥 Light-gated 🟨 Voltage-gated 🟦 Tension-gated 🟩 Ligand/Chemical-gated ⬜ Temperature/pH-gated

Acknowledgments

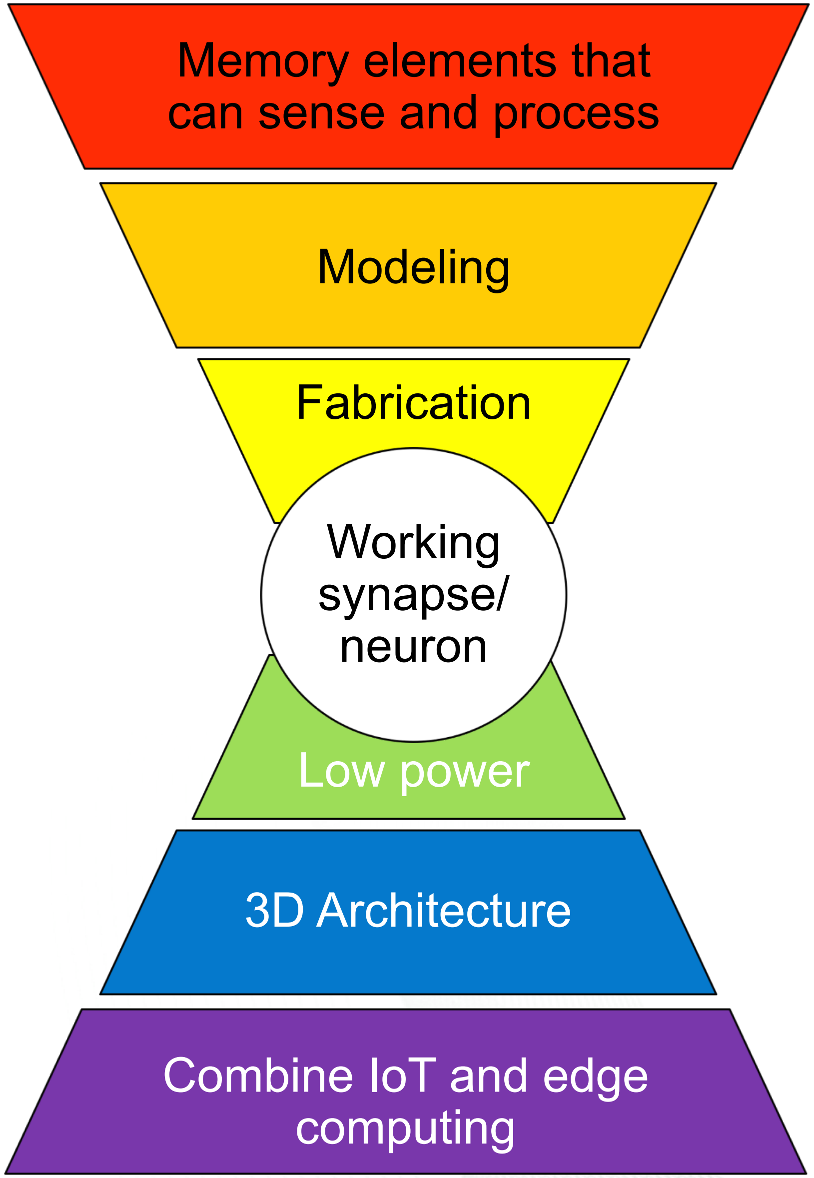
We would like to thank:

- Oak Ridge National Laboratory for funding this work
- Oak Ridge Leadership Computing Facility for providing computing support
- The National Science Foundation for funding this work
- Dr. R. Stanley Williams for his valuable input, suggestions, and insights

If you have any questions or suggestions please send me an email at
najemjs@ornl.gov

Why ORNL, Why Now?

- **Oak Ridge National Lab** is a national **leader** in **computation** and **materials research**
- We are approaching the end of **Moore's law** era.
- The reliability of the IoT, edge, and cloud computing in **exponentially growing**.
- **Power consumption** and **environmental considerations** are the main problems humanity faces this century
- **Crosscutting efforts** in chemistry, biology, engineering and computation (with all the right people and ingredients available locally)
- Insight into the evolutionary path of many species



Memory elements that can sense and process

Modeling

Fabrication

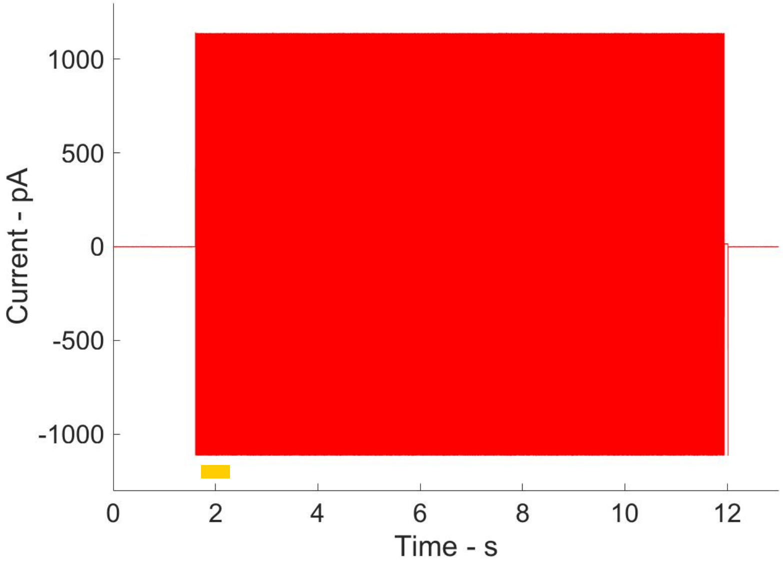
Working synapse/ neuron

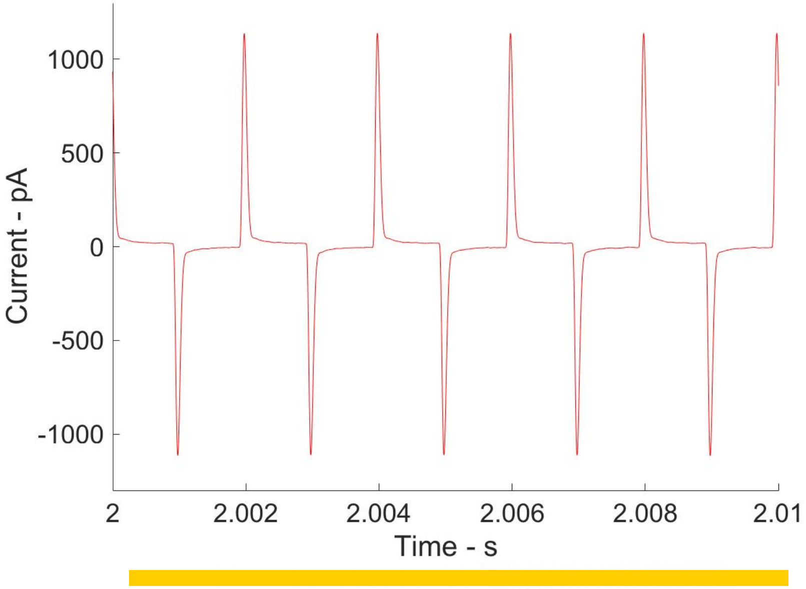
Low power

3D Architecture

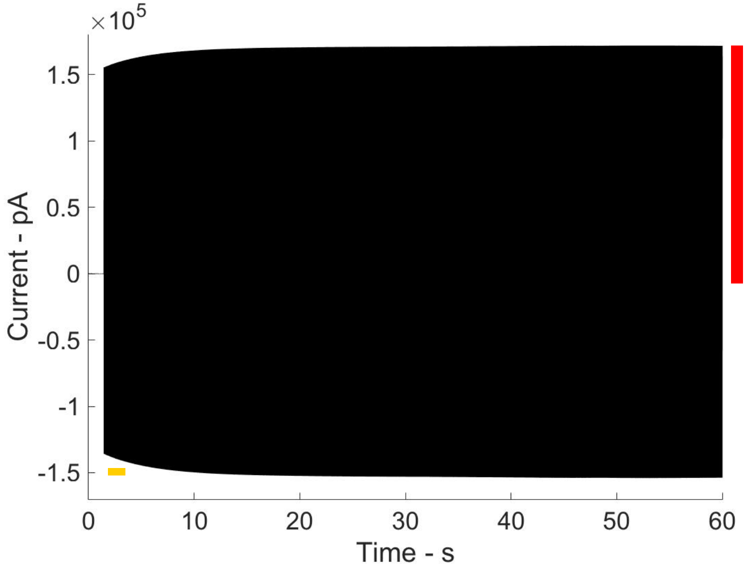
Combine IoT and edge computing

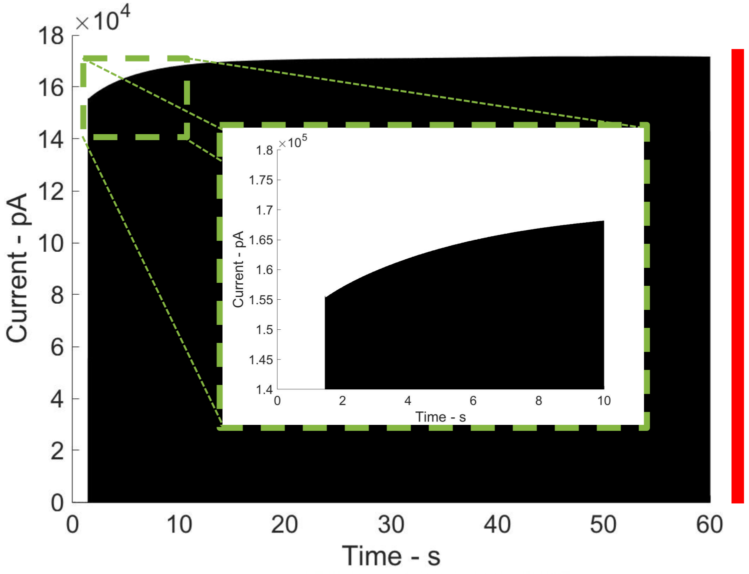
Response to pulses – control





Response to pulses – Hexadecane at RT





Pulse amplitude = 150 mV

Pulse width = 2ms

Off-time= 2ms