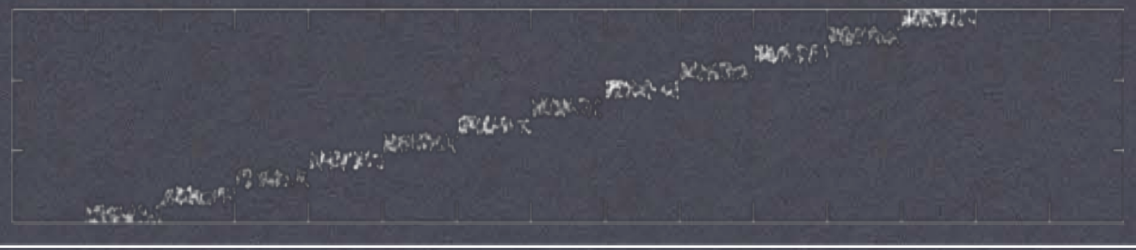
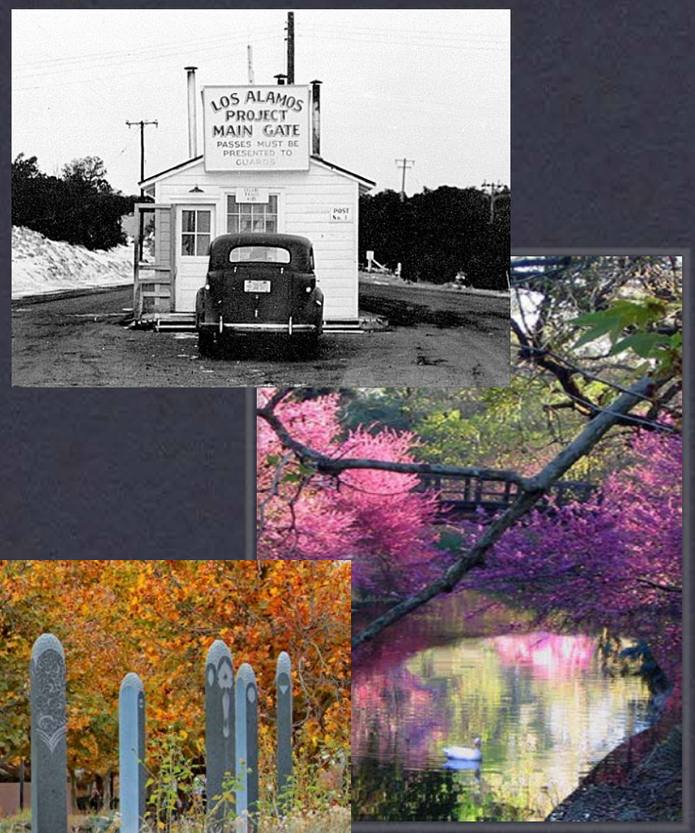


A Pulse-Gated, Neural Implementation of the Backpropagation Algorithm

Jordan Snyder, Anatoly Zlotnik, Andrew Sornborger, Louis Tao

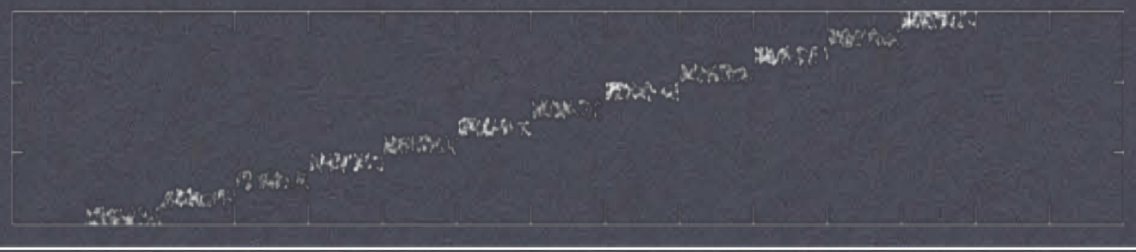


NICE 2019, SUNY ALBANY

LA-UR-19-22463

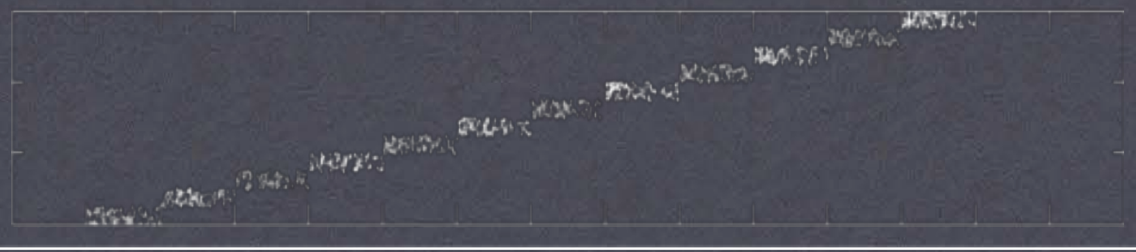
WHAT I CANNOT CREATE, I DO NOT UNDERSTAND

Motivation



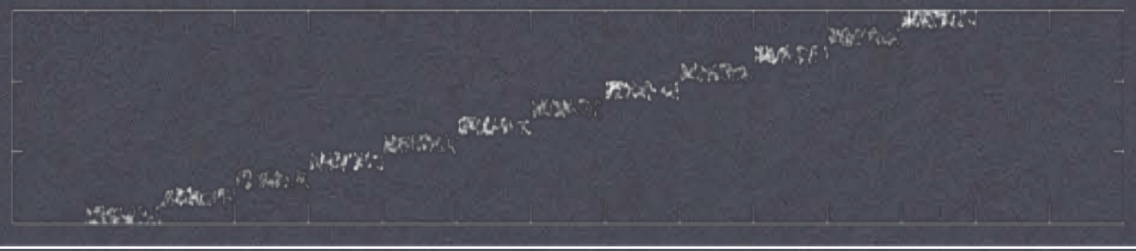
- *DEEP NEURAL NETS ARE THE WORKHORSE FOR CURRENT MACHINE LEARNING*
- *DEEP NETS ARE BASED ON THE BACKPROPAGATION ALGORITHM*
- *ALTHOUGH INSPIRED BY NEURAL SYSTEMS, BACKPROP IS INHERENTLY DIFFICULT TO IMPLEMENT IN A NEURAL CIRCUIT DUE TO NON-LOCAL LEARNING*
- *MIKE DAVIES SAID IT COULDN'T BE DONE…*

Outline



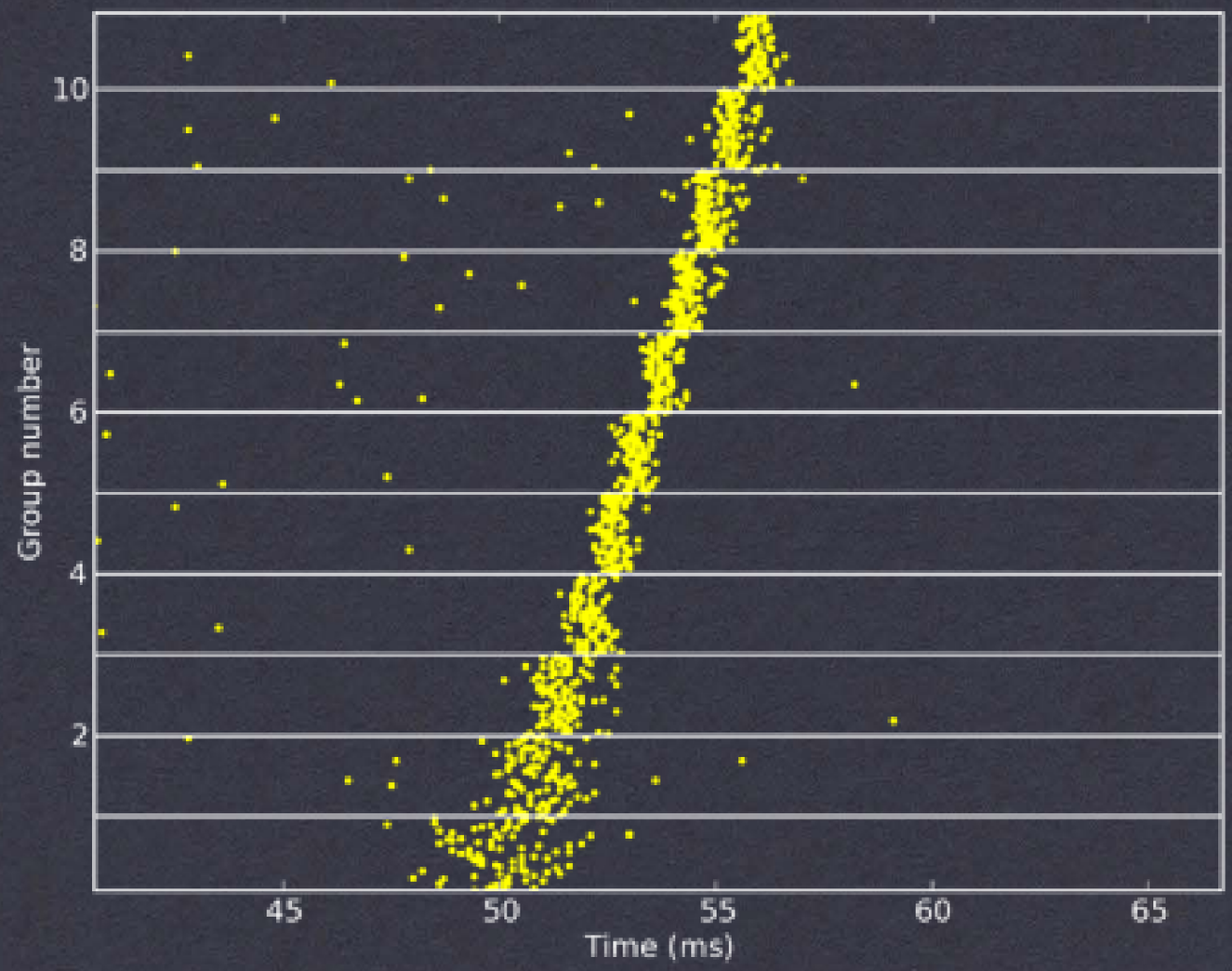
- *BACKGROUND: SYNFIRE CHAINS*
- *SYNFIRE-GATED SYNFIRE CHAINS (SGSCS) FOR GRADED INFORMATION PROPAGATION*
- *HOW TO COMPUTE WITH SGSCS*
- *LEARNING*
- *BACKPROP*

Synfire chains



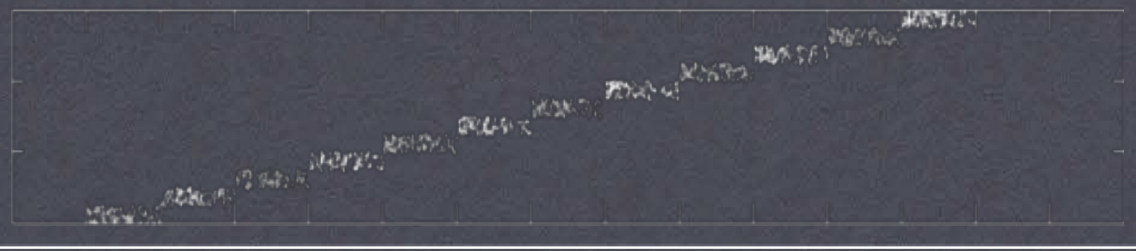
SYNFIRE CHAIN

ABELES 1982



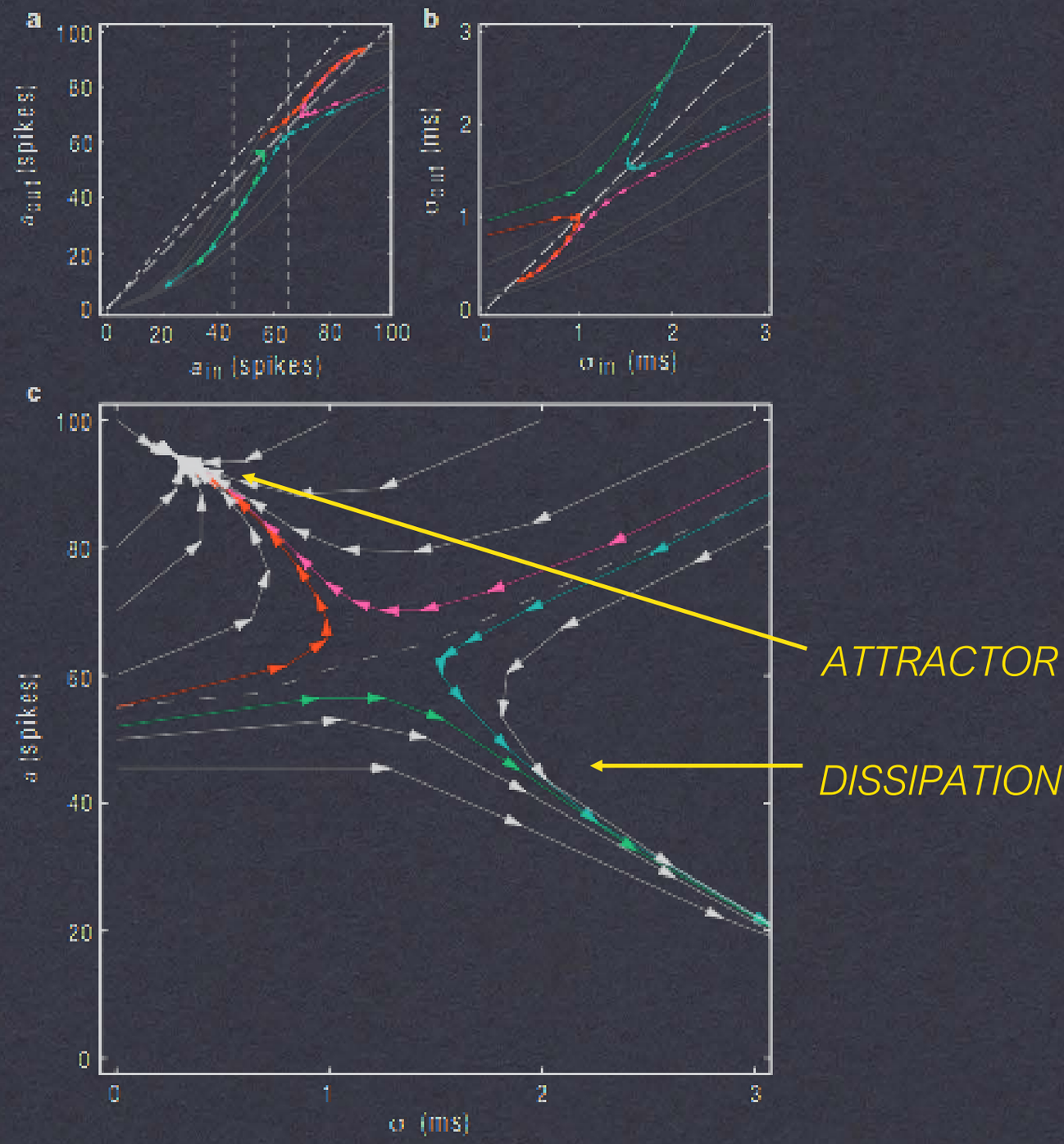
BRIANSIMULATOR.ORG

Synfire chains



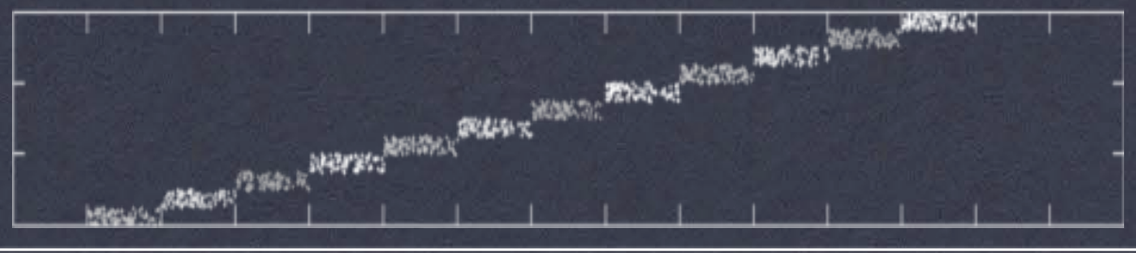
ORIGINAL HOPE: TO PROPAGATE GRADED INFORMATION WITH SYNFIRE CHAINS I.E. LAYERS WITH FEEDFORWARD CONNECTIVITY

- CAN'T PROPAGATE GRADED INFORMATION THIS WAY

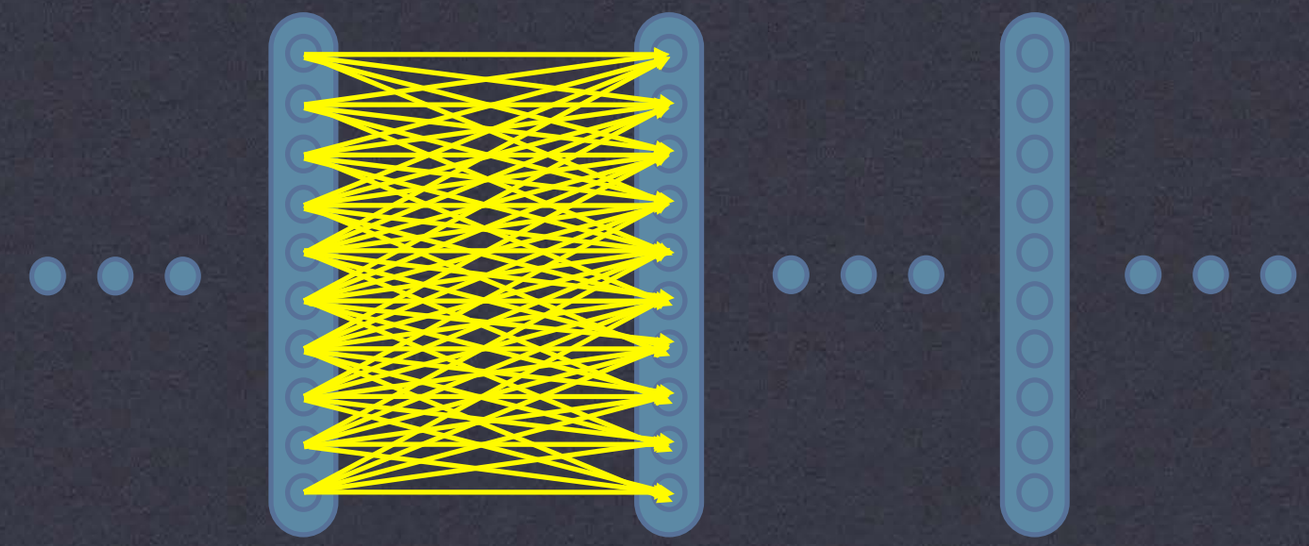


DIESMANN, GEWALTIG, AERTSEN, NATURE, 1999

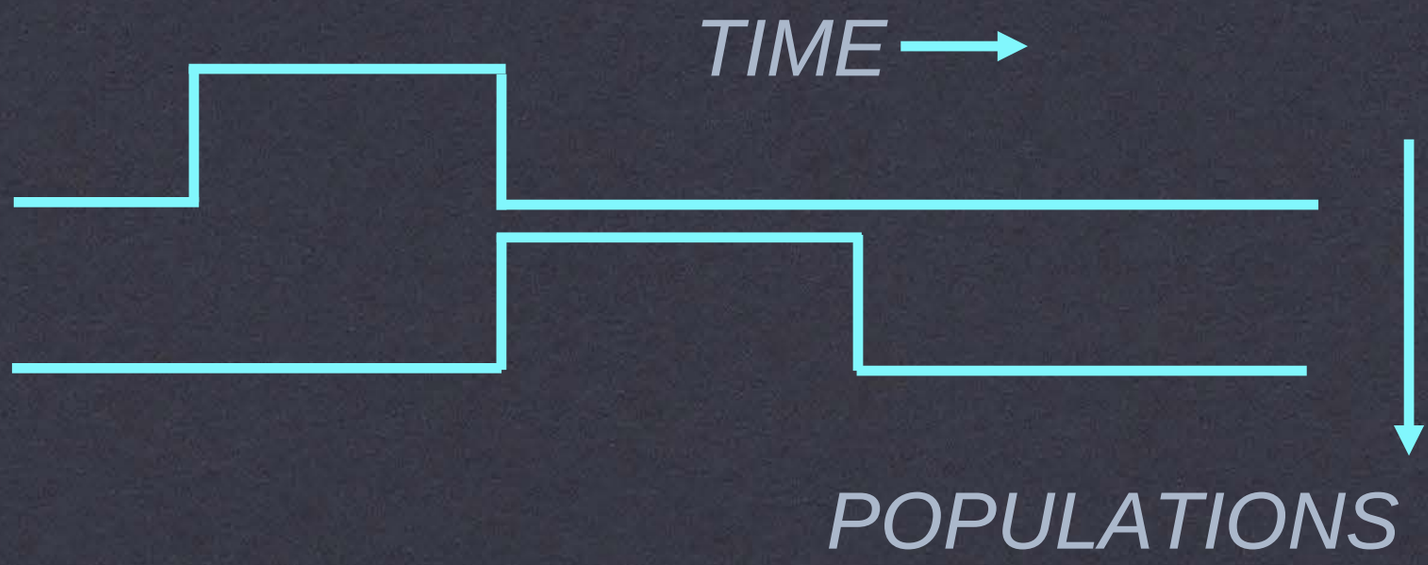
Synfire-gated synfire chains



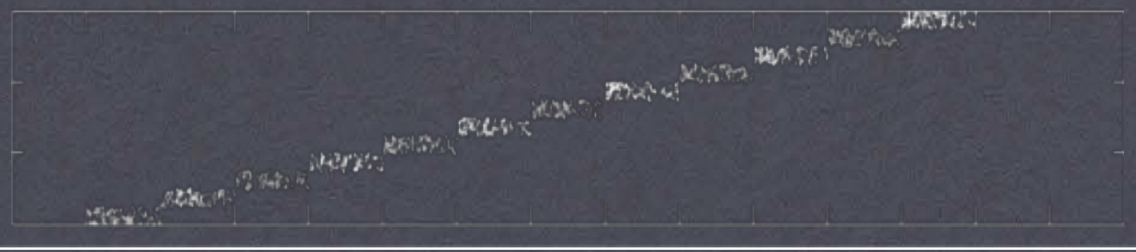
FEED-FORWARD CHAIN OF NEURONS



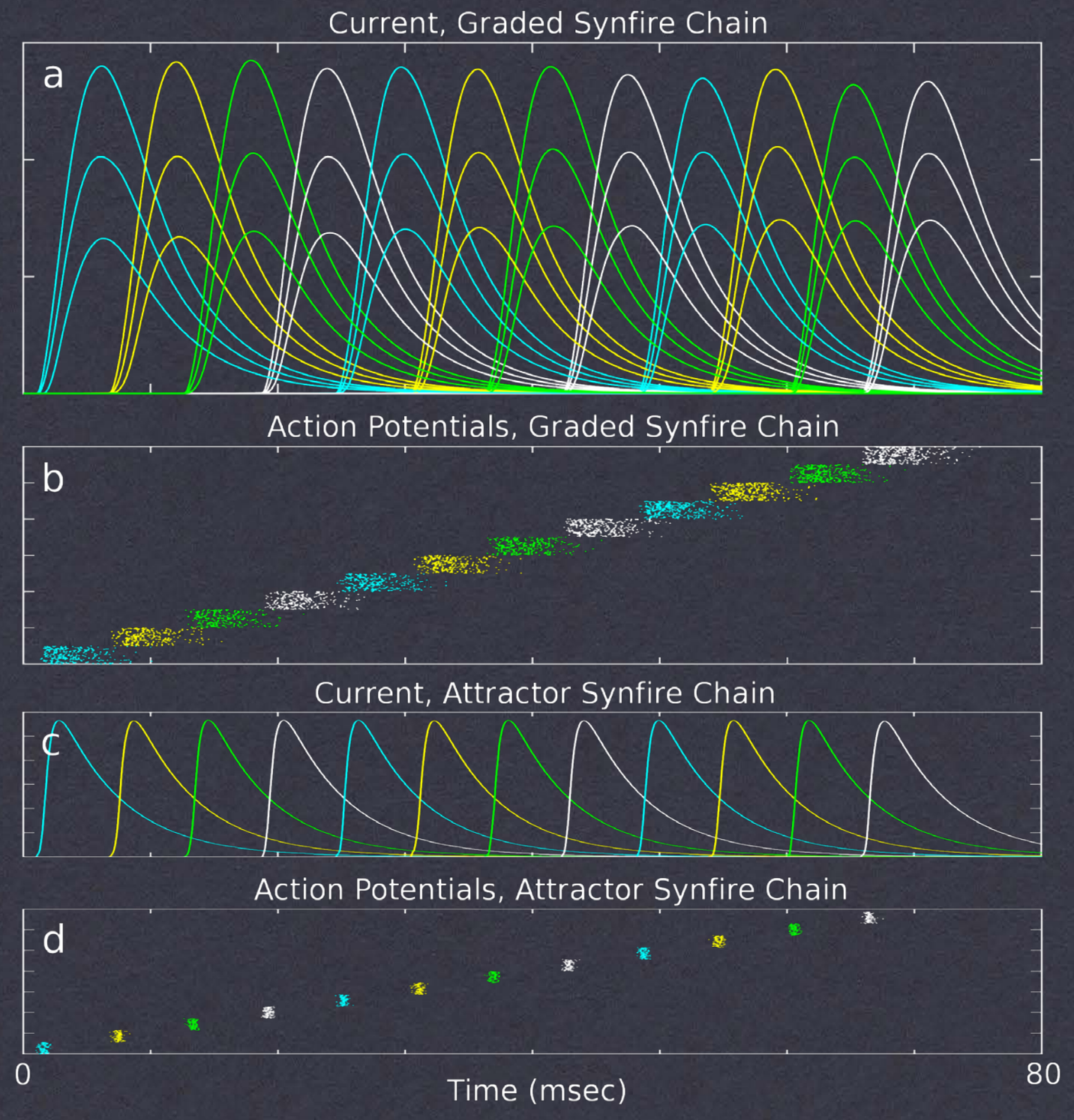
PRECISE TEMPORAL SEQUENCE OF GATING PULSES



Synfire-gated synfire chains

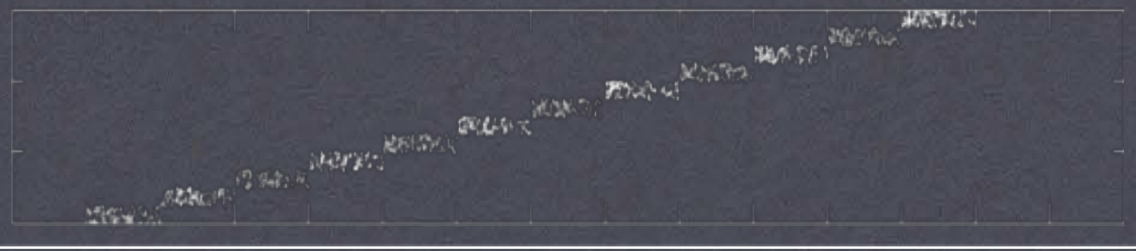


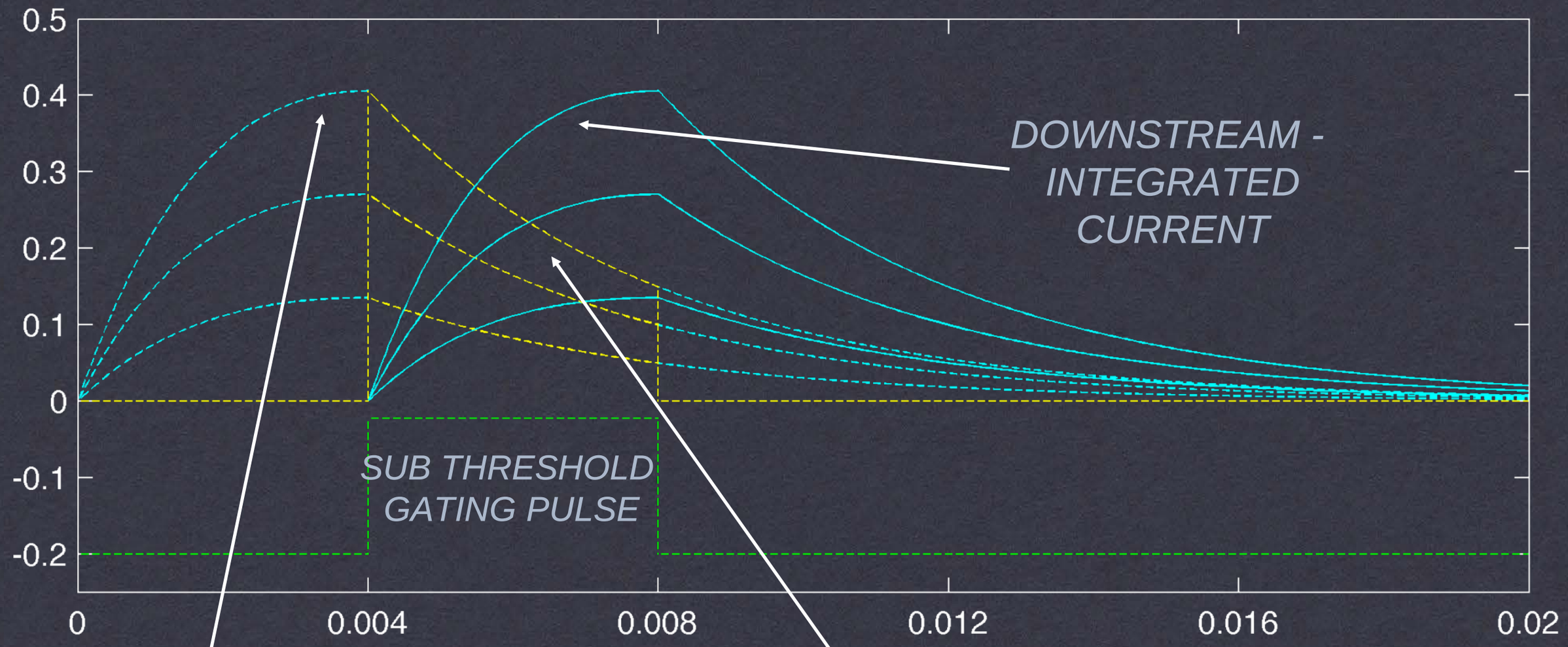
MECHANISM: USE NEURAL POPULATIONS IN A CONVENTIONAL SYNFIRE CHAIN (I.E. ONE THAT APPROACHES AN ATTRACTOR) AS A PULSE GENERATOR TO PUSH SECONDARY POPULATIONS ABOVE THRESHOLD



WANG, SORNBORGER, TAO
PLOS COMP BIO (2016)

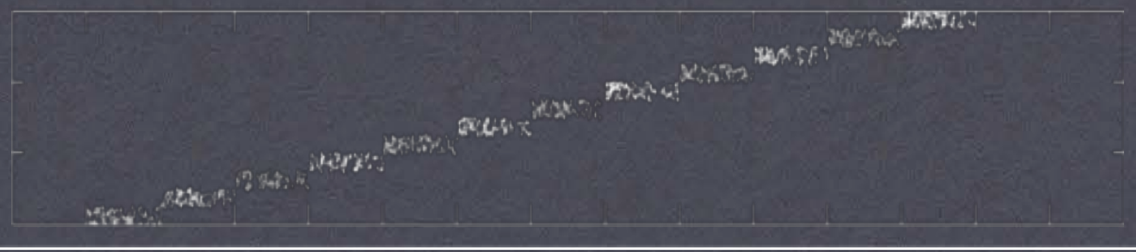
SGSC: A mean field model





SORNBORGER, WANG, TAO, JCNS (2015)

Thresholded Linear Maps



PULSE-GATED PROPAGATION BETWEEN VECTORS OF POPULATIONS

$$\tau \frac{d}{dt} I^d = -I^d + S\left[K I^u + p^u(t)\right]^+$$

FIXED CONNECTIVITY

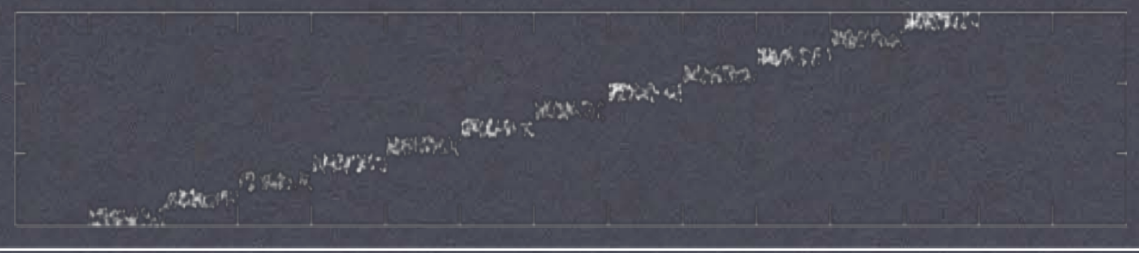
DYNAMIC ROUTING

LEADS TO FEED-FORWARD NEURAL CIRCUITS WITH ACTIVELY GATED LINEAR MAPS

$$\mathbf{I}^u(t) \xrightarrow{K} \mathbf{I}^d(t)$$

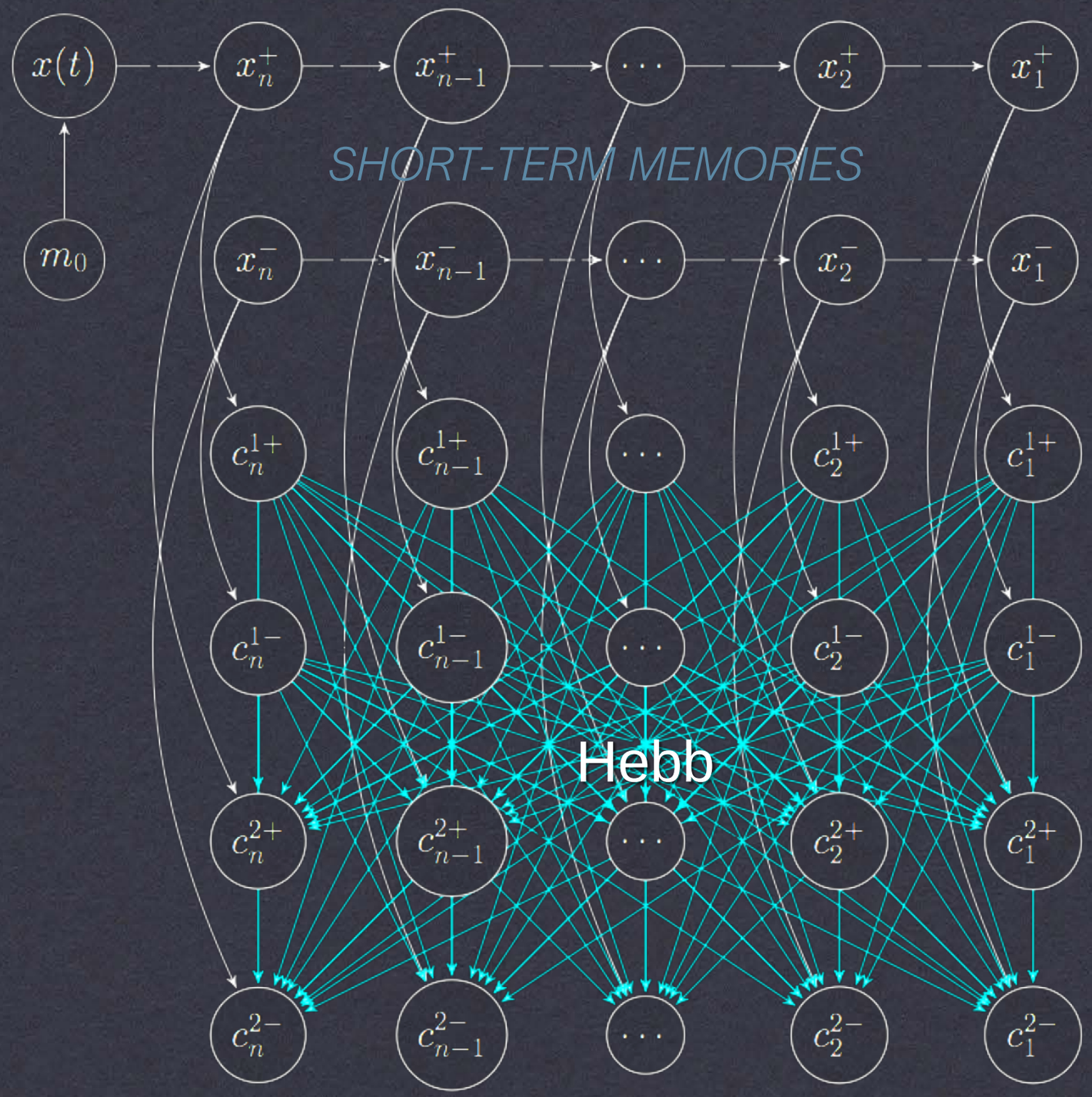
SORNBORGER, WANG, TAO, JCNS (2015)

Learning a Lagged-Covariance



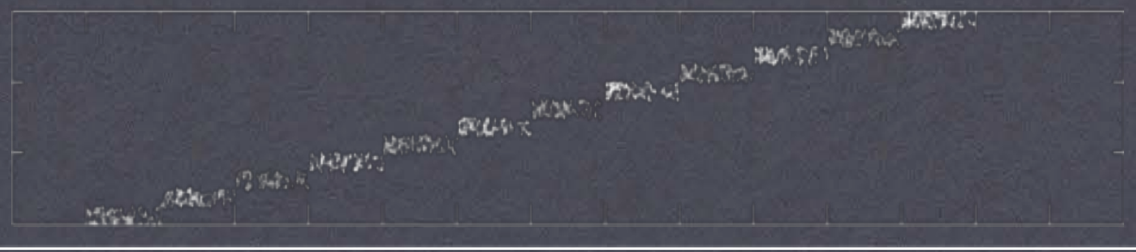
AUTOREGRESSIVE AR(2) PROCESS INPUT

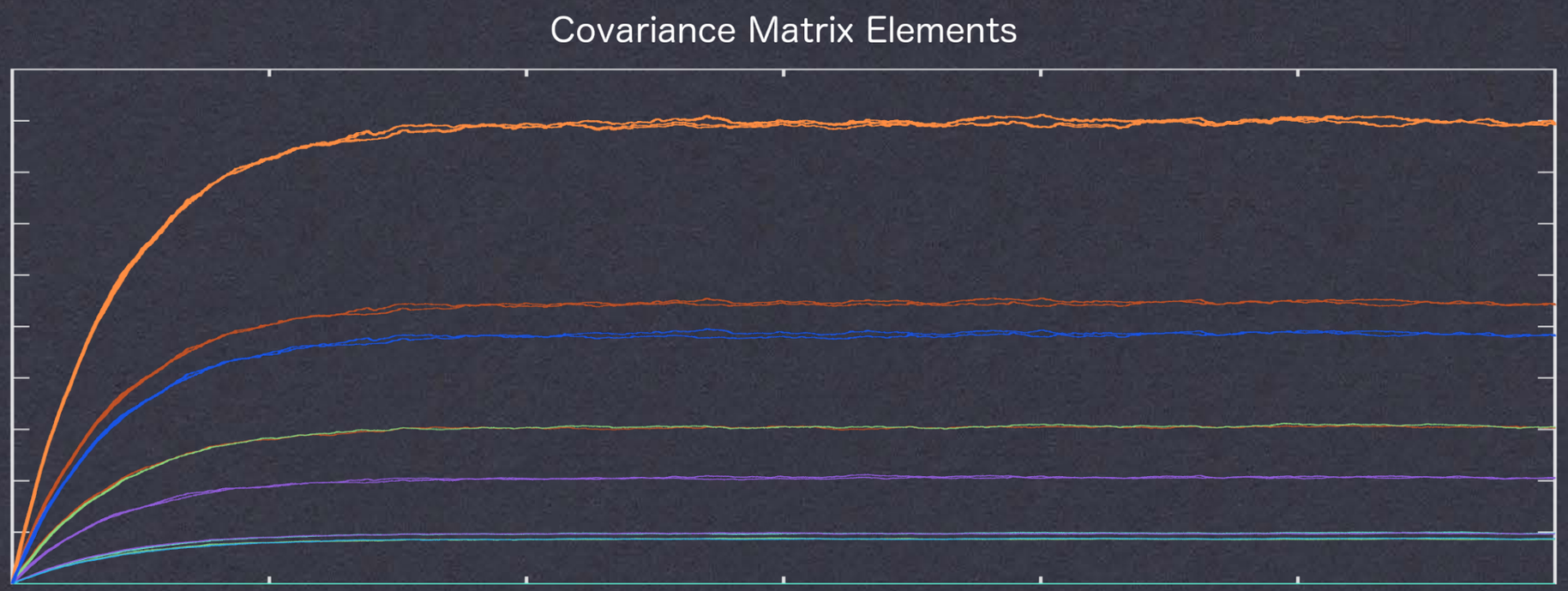
SIMULTANEOUSLY GATE INFORMATION TO PRE- AND POST-SYNAPTIC SIDES OF SYNAPTIC CONNECTIONS



SHAO, SORNBORGER, TAO, *50th Asilomar Conference* (2016)

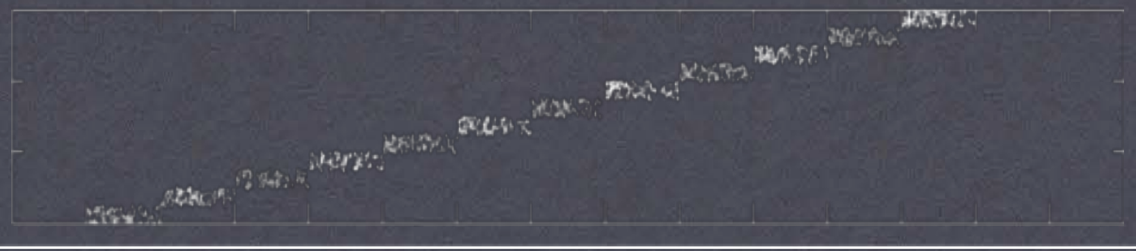
Learning





SHAO, SORNBORGER, TAO, *50th Asilomar Conference* (2016)

PMPY

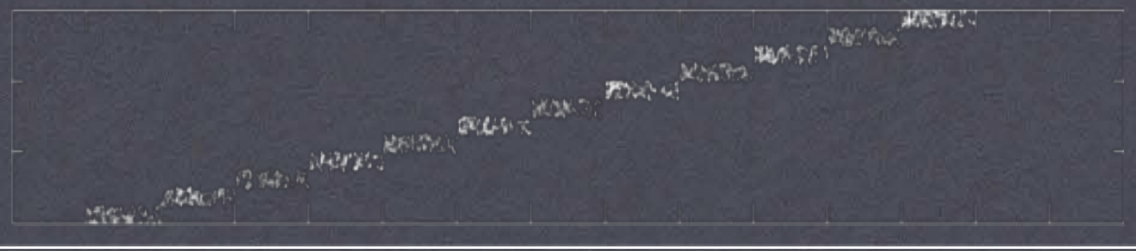


CORRESPONDENCE BETWEEN STANDARD AND PMPY PROTOCOL

Standard Protocol	Push-me Pull-you Protocol
$o_0 = x$	$o_0 = \begin{bmatrix} r(x) \\ r(-x) \end{bmatrix}$
$n_i = W_i o_{i-1}$	$n_i = r(W_i' o_{i-1}) - r(-W_i' o_{i-1}) \equiv n_i^+ - n_i^-$
$o_i = r(n_i)$	$o_i = r(n_i^+ - n_i^-)$
$p_i = r'(n_i)$	$p_i = r'(n_i^+ - n_i^-) \circ r'(W_i' o_{i-1}) - r'(n_i^+ - n_i^-) \circ r'(-W_i' o_{i-1}) \equiv p_i^+ - p_i^-$
$\delta_I = (o_I - t) \circ p_I$	$\delta_I = r(o_I - t) \circ p_i^+ + r(o_I - t) \circ p_i^- - r(t - o_I) \circ p_i^+ - r(t - 0_I) \circ p_i^- \equiv \delta_I^{++} + \delta_I^{+-} - \delta_I^{-+} - \delta_I^{--}$
$\delta_{i-1} = W_i^T \delta_i \circ p_{i-1}$	$\delta_{i-1} = r(W_i \delta_i) \circ p_{i-1}^+ + r(W_i \delta_i) \circ p_{i-1}^- - r(-W_i \delta_i) \circ p_{i-1}^+ - r(-W_i \delta_i) \circ p_{i-1}^- \equiv \delta_{i-1}^{++} + \delta_{i-1}^{+-} - \delta_{i-1}^{-+} - \delta_{i-1}^{--}$
$\Delta W = \delta_i o_{i-1}^T$	$\Delta W_i^+ = (\delta_i^{++} - \delta_i^{-+}) o_{i-1}^T$ $\Delta W_i^- = -(\delta_i^{--} + \delta_i^{+-}) o_{i-1}^T$

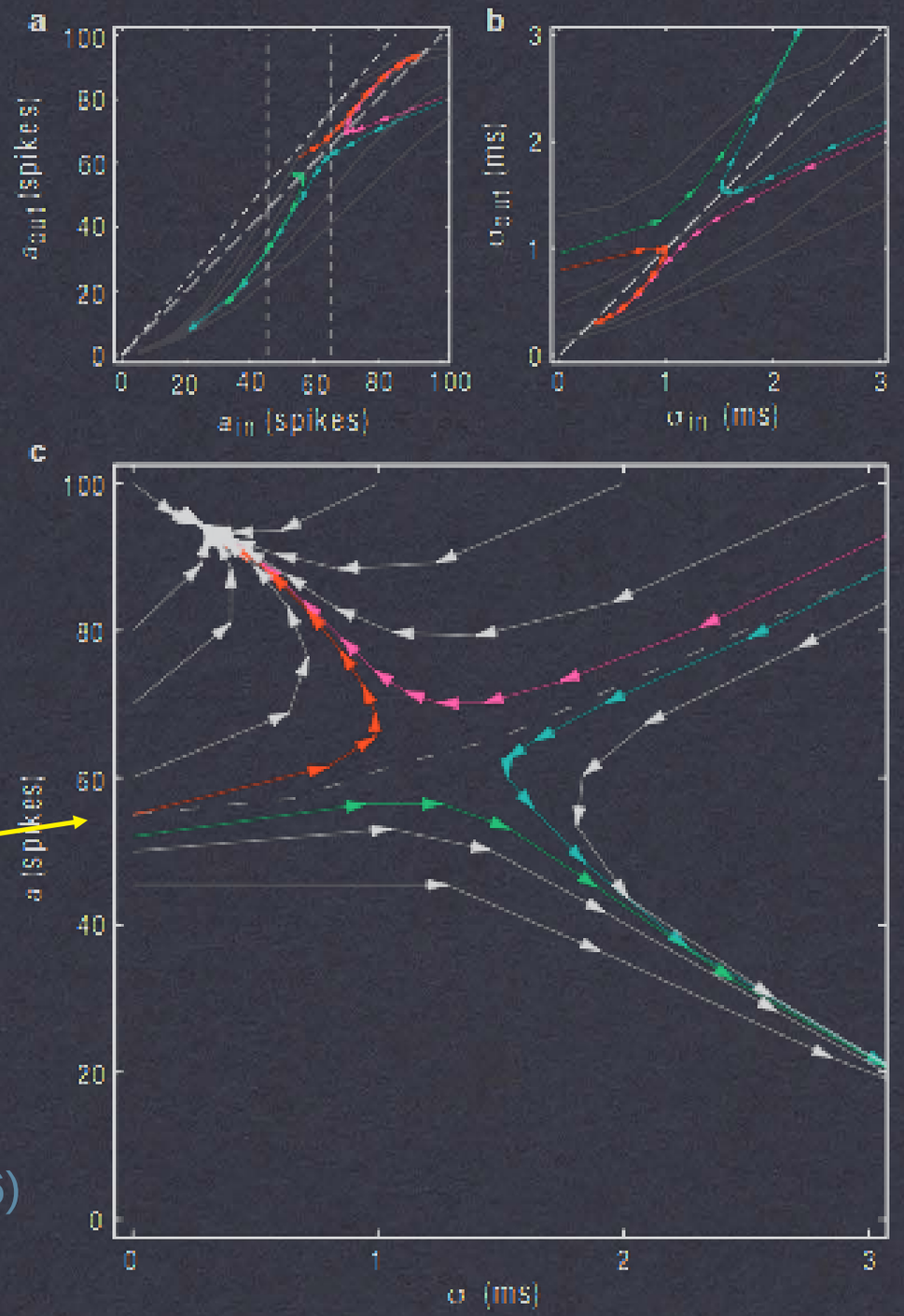
SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

ReLU Derivatives



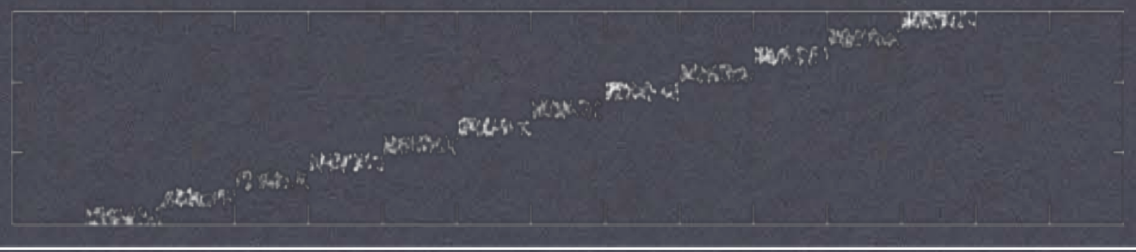
DERIVATIVE (HEAVISIDE FUNCTION) VIA INTERACTION OF GRADED AND GATING CHAINS

FEED OUTPUT FROM GRADED CHAIN INTO GATING CHAIN, THIS CREATES A PULSE SET BY LOCATION OF SEPARATRIX



WANG, SORNBORGER, TAO, *PLOS COMPUT BIOL* (2016)

Backprop

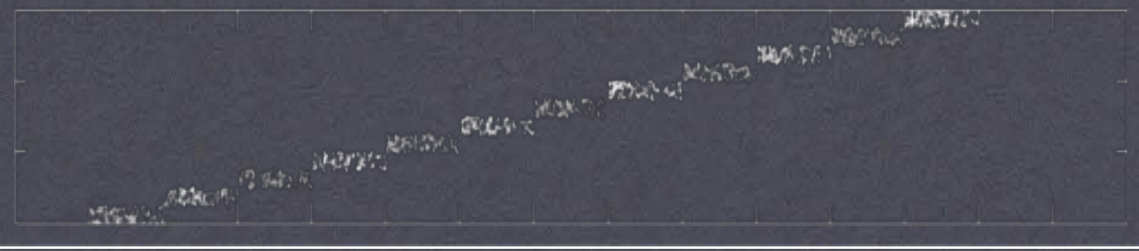


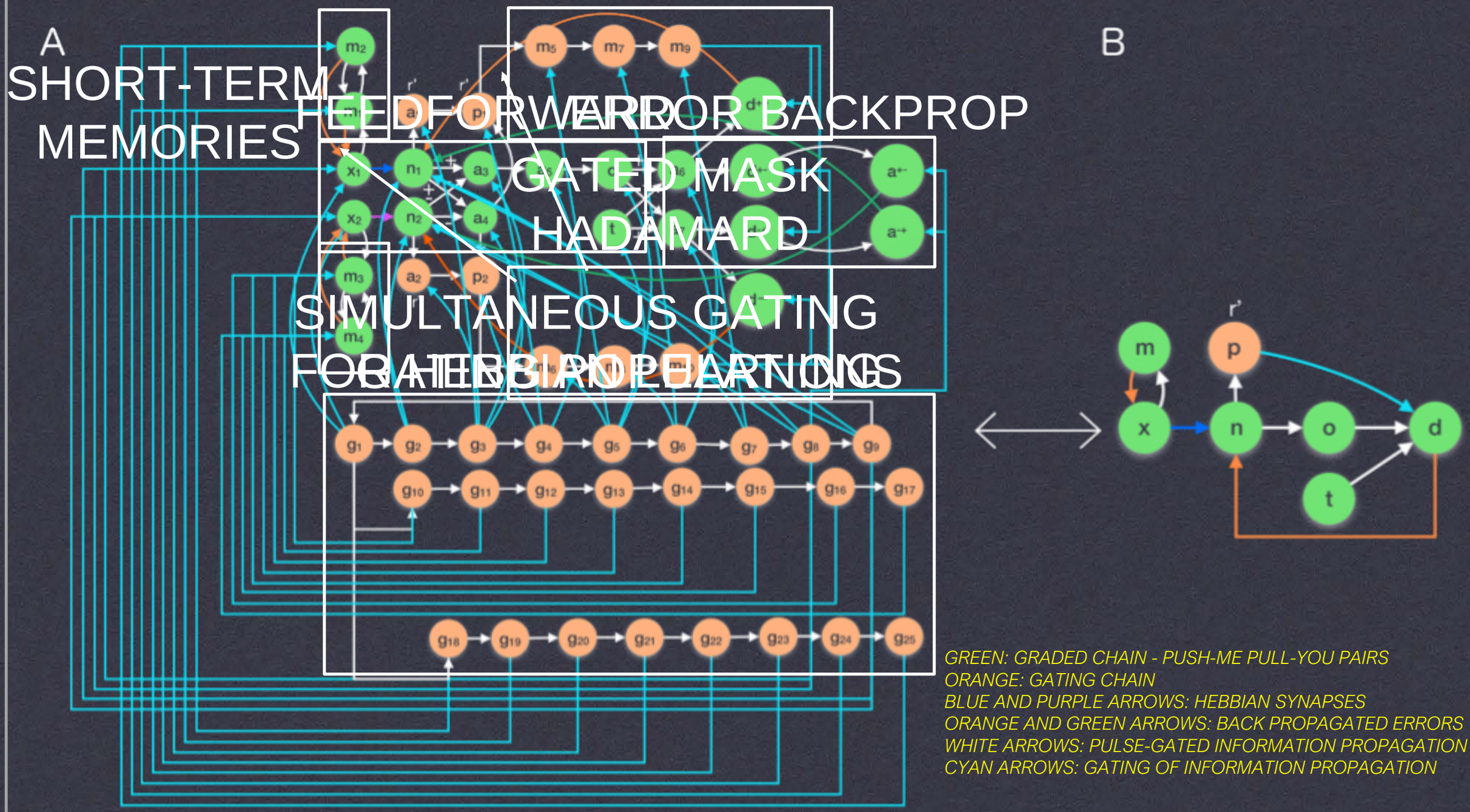
NEURAL AND NETWORK MECHANISMS FOR IMPLEMENTING BACKPROP:

- *SYNFIRE-GATED SYNFIRE CHAIN(S)*
- *SHORT-TERM MEMORIES*
- *PUSH-ME PULL-YOU PAIRS FOR ENCODING REAL NUMBERS*
- *GATING OF RELU THRESHOLDED ACTIVITY*
- *GATING OF DERIVATIVE OF RELU (THETA FUNCTION) ACTIVITY VIA SGSC*
- *IMPLEMENTATION OF HADAMARD PRODUCT VIA PULSE-GATING*
- *SIMULTANEOUS GATING OF GRADED INFORMATION TO PRE- AND POST-SYNAPTIC NEURONAL POPULATIONS FOR HEBBIAN SYNAPTIC UPDATE (TURNING LEARNING ON AND OFF VIA PULSE-GATED CONTROL)*

SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

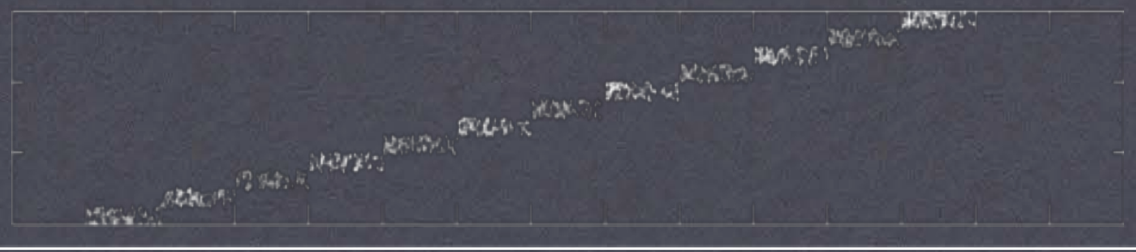
Backprop



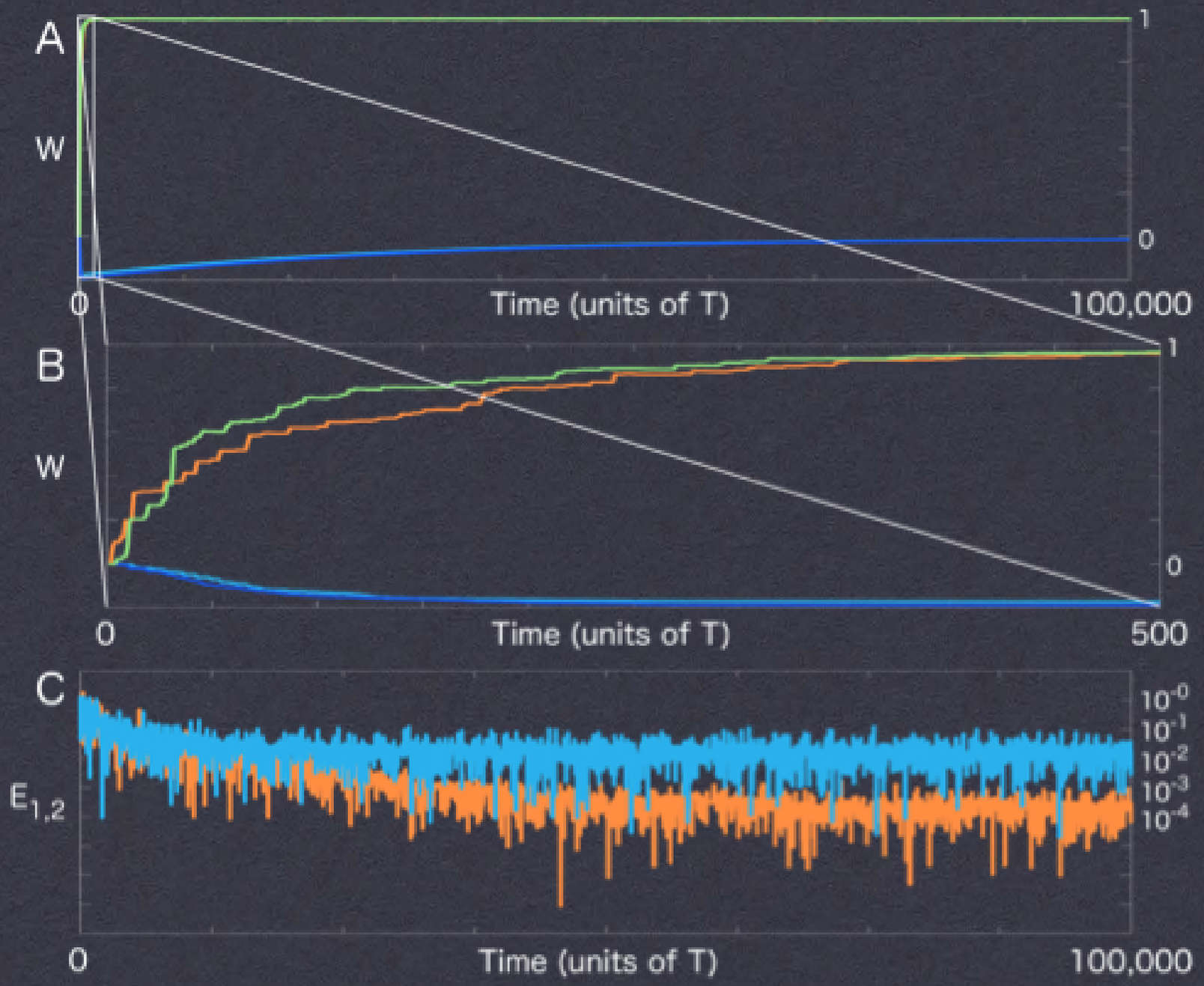


SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

Backprop

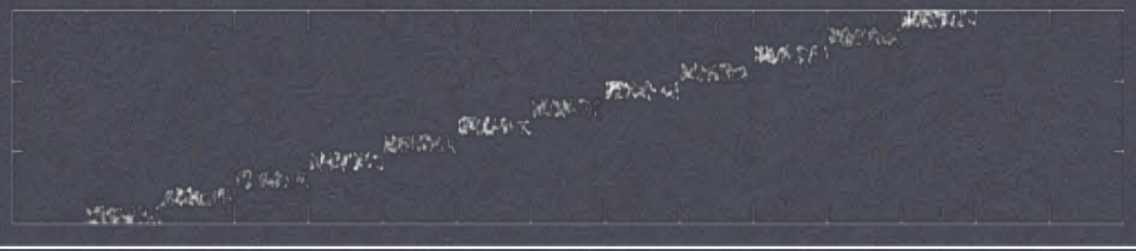


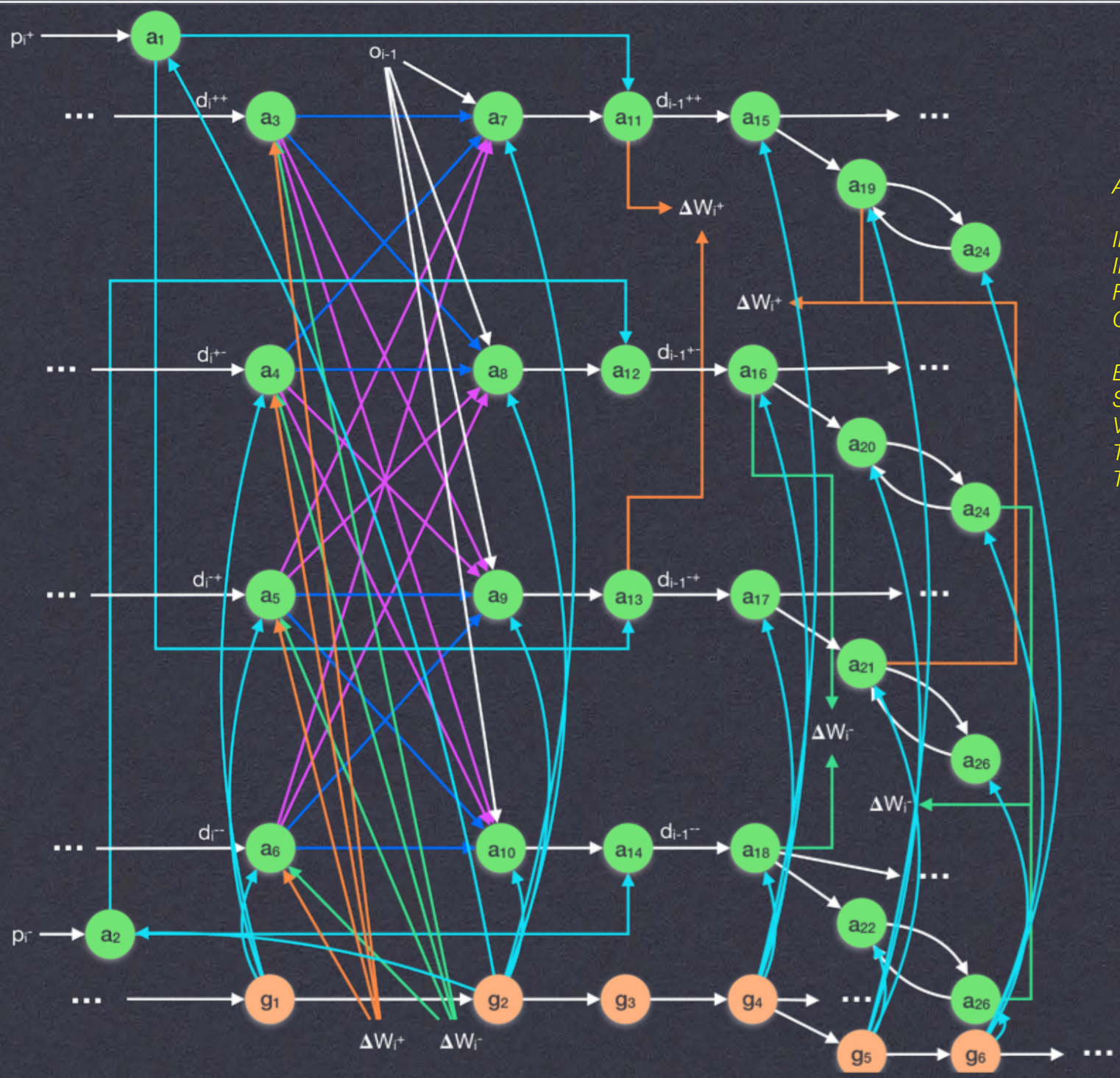
LEARNING A LINEAR TRANSFORM WITH A SINGLE PUSH-ME PULL-YOU PAIR



SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

Backprop





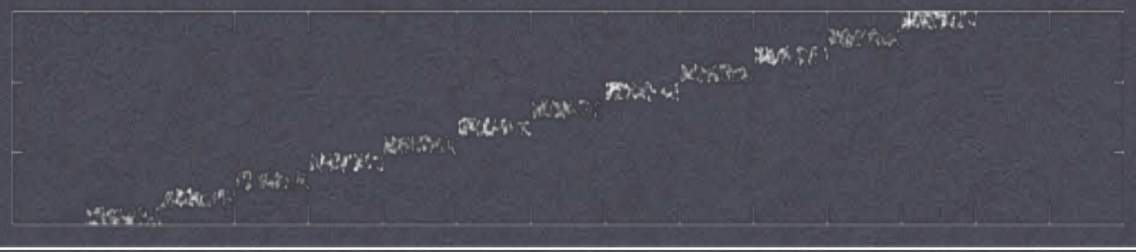
A LAYER FOR THE BACK PROPAGATION OF ERRORS:

INCOMING GATING PULSES REPRESENTING MASKED INFORMATION FROM THE DERIVATIVE OF THE ACTIVITY FUNCTION IS PROPAGATED THROUGH THE PART OF THE CIRCUIT RESPONSIBLE FOR ERROR PROCESSING.

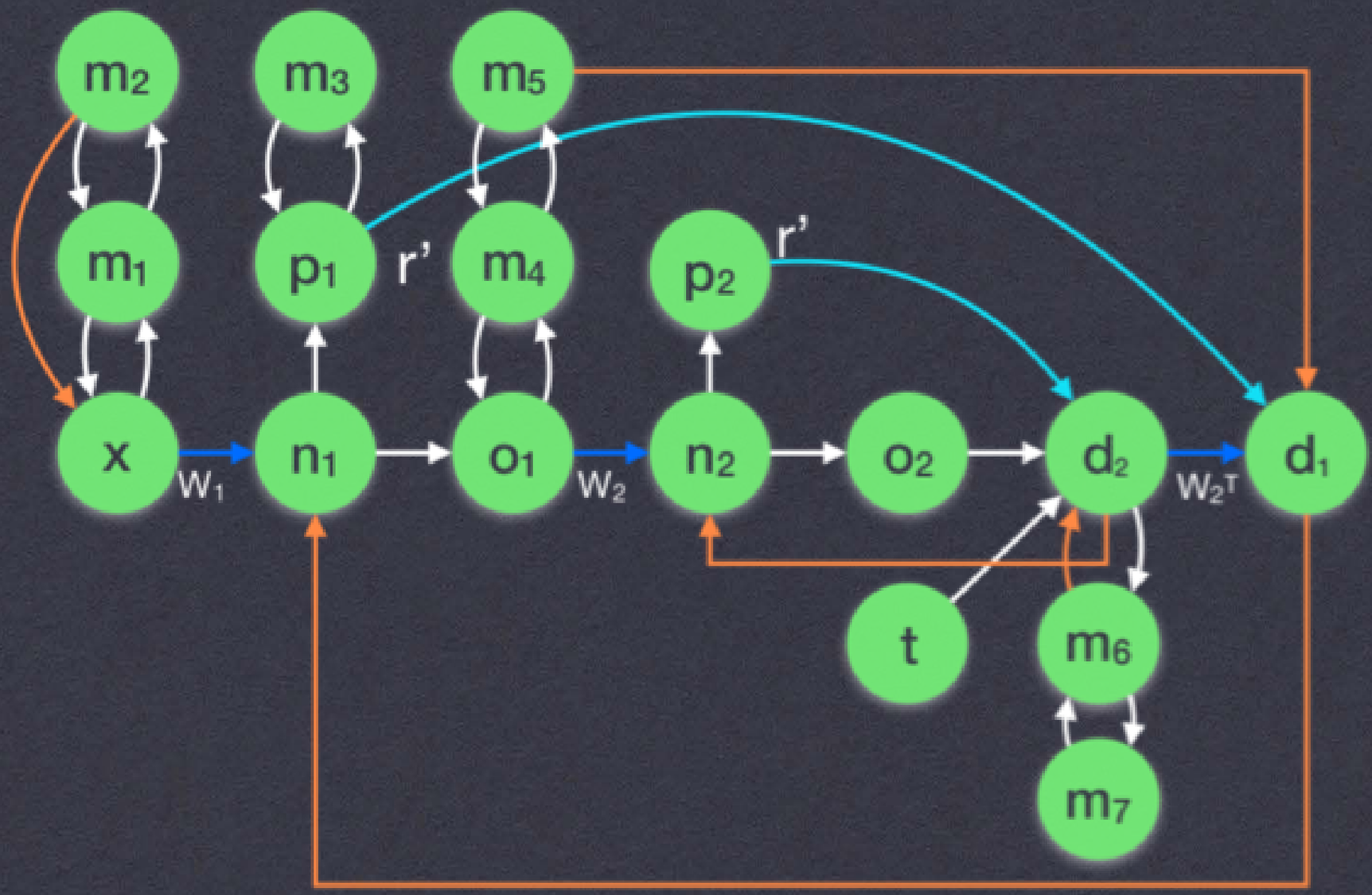
ERRORS ARE COMPUTED AND ROUTED TO PRE- AND POST-SYNAPTIC NEURONAL POPULATIONS FOR SYNAPTIC UPDATE VIA HEBBIAN LEARNING. THIS INCLUDES POPULATIONS IN THE ERROR COMPUTATION CIRCUIT REQUIRING COPIES OF THE TRANSPOSED WEIGHTS.

SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

Backprop

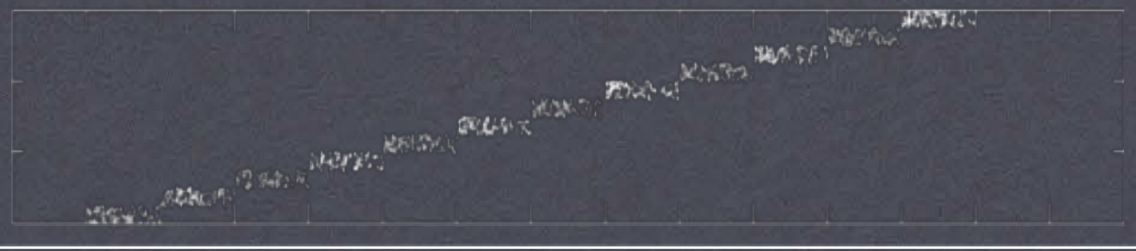


CONNECTIVITY AND GATING SCHEMATIC FOR TWO-LAYER CIRCUIT FOR LEARNING XOR LOGIC

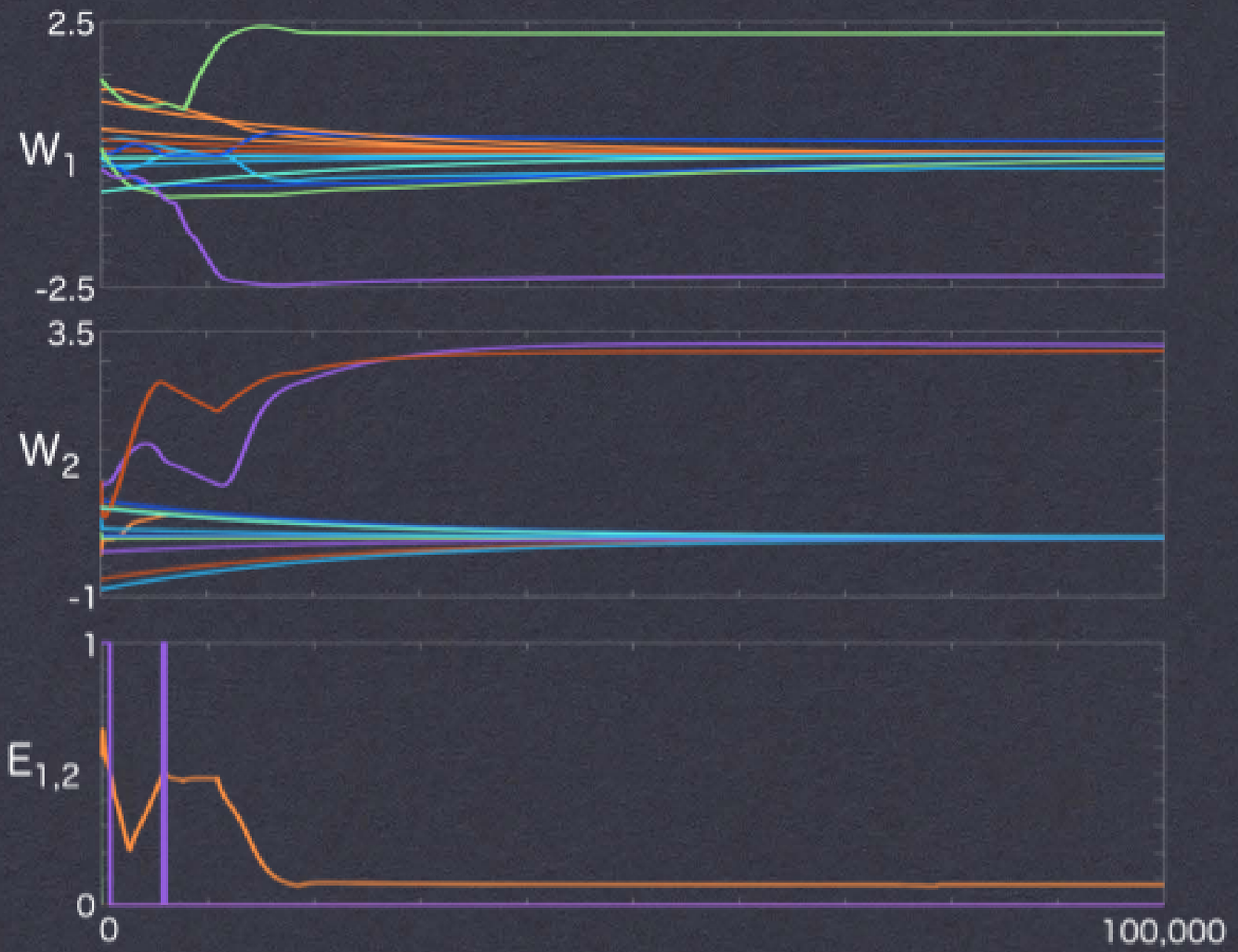


SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

Backprop

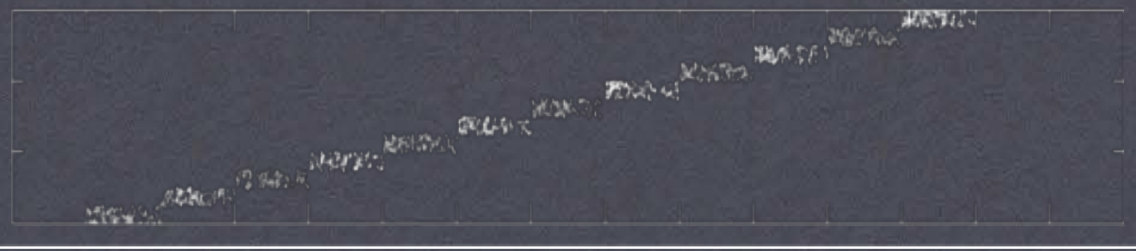


RESULTS OF LEARNING THE XOR LOGICAL FUNCTION IN A TWO-LAYER CIRCUIT



SNYDER, ZLOTNIK, SORNBORGER, TAO, *bioRxiv* (2019)

Conclusions



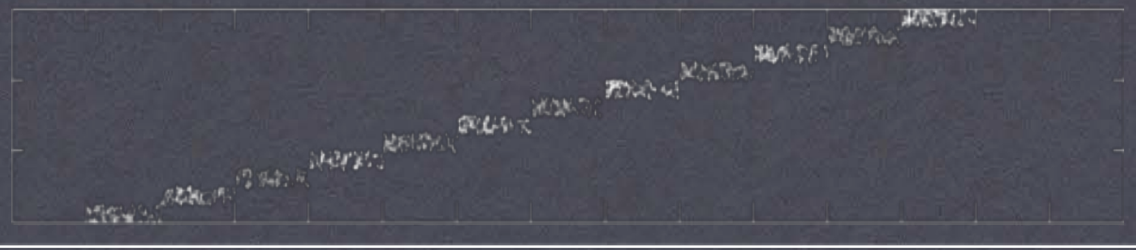
- *USING PULSE-GATING TO PRECISELY CONTROL INFORMATION PROPAGATION, EFFECTIVE ACTIVITY FUNCTIONS, AND LEARNING, WE HAVE IMPLEMENTED THE BACKPROPAGATION ALGORITHM IN A MEAN-FIELD NEURAL CIRCUIT*

- *THE BACKPROP NEURAL CIRCUIT OVERCOMES THE PROBLEMS OF NON-LOCAL LEARNING USING AN SGSC-BASED OPERATING SYSTEM THAT CONTROLS THE PROPAGATION OF INFORMATION AS IT FLOWS THROUGH THE CIRCUIT, ALLOWING LEARNING TO BE TURNED ON AND OFF AT APPROPRIATE TIMES*

Los Alamos NATIONAL LABORATORY EST. 1943

WHAT I CANNOT CREATE, I DO NOT UNDERSTAND

Questions?



WHAT I CANNOT CREATE,
I DO NOT UNDERSTAND