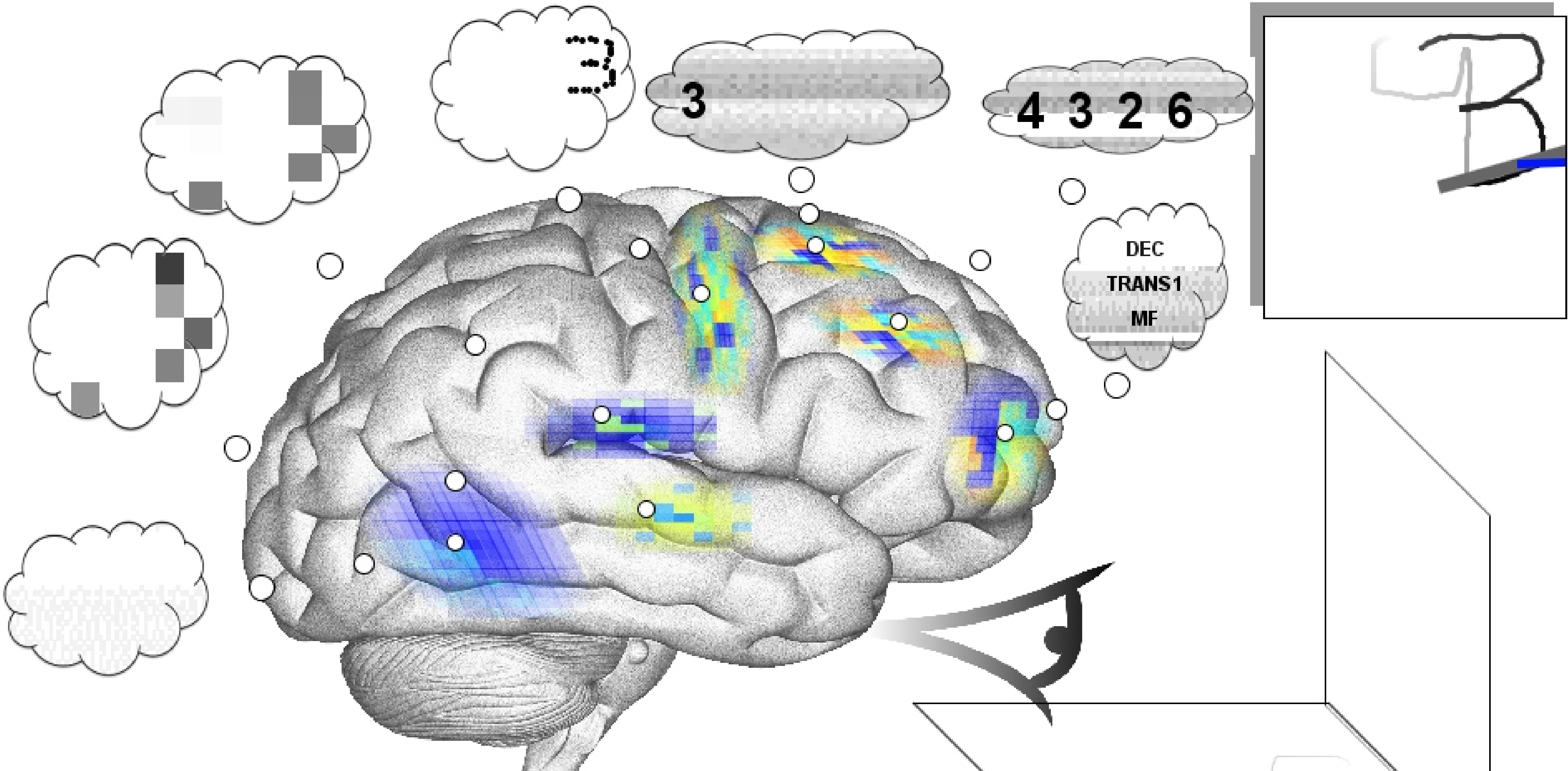
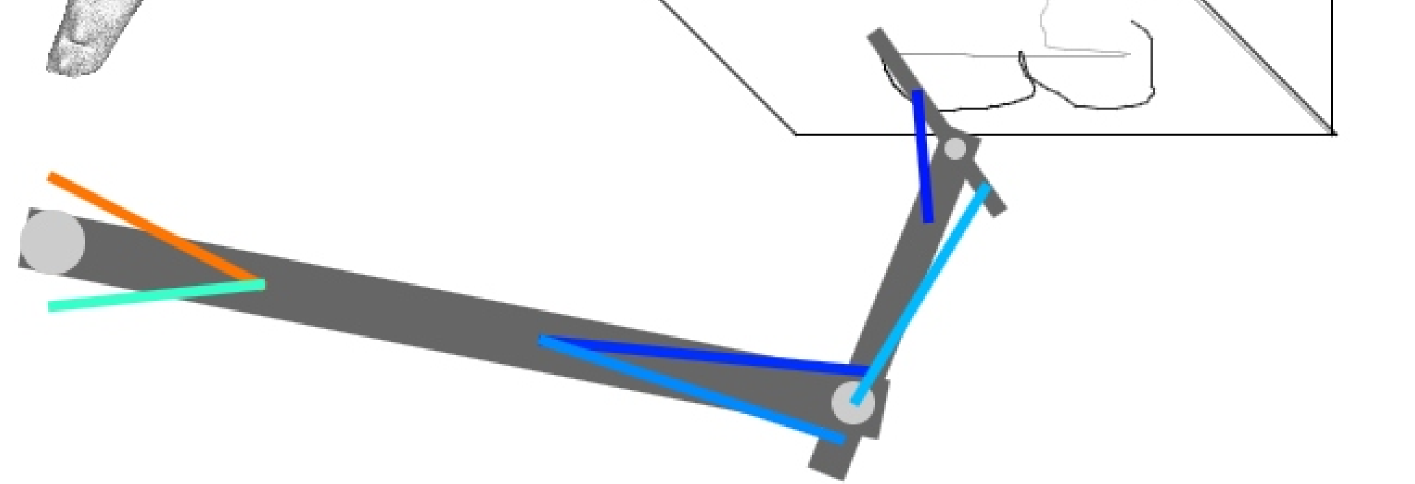




Implementing high-order cognition in neuromorphic hardware

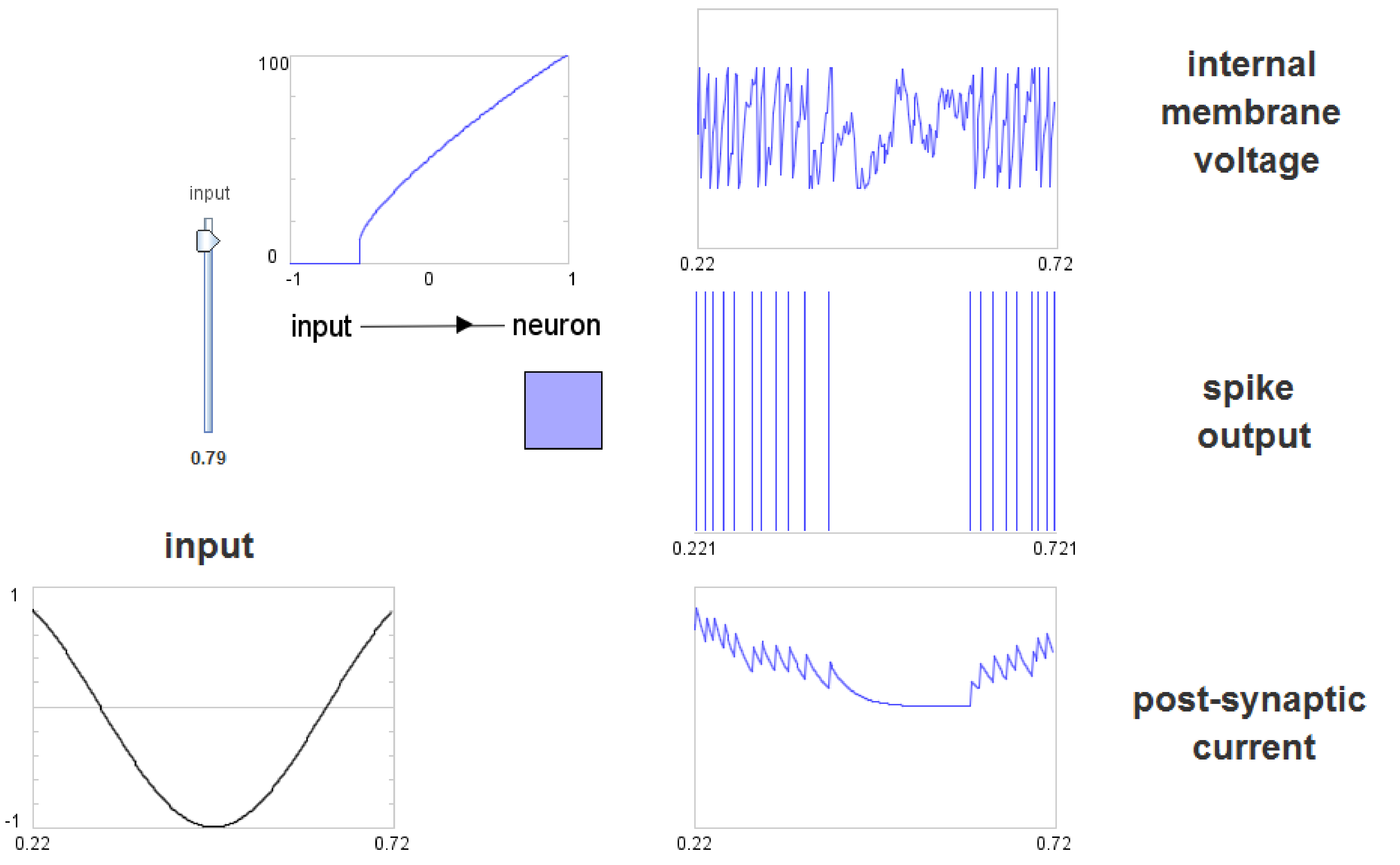
Terrence C. Stewart
Chris Eliasmith

Centre for Theoretical Neuroscience,
University of Waterloo

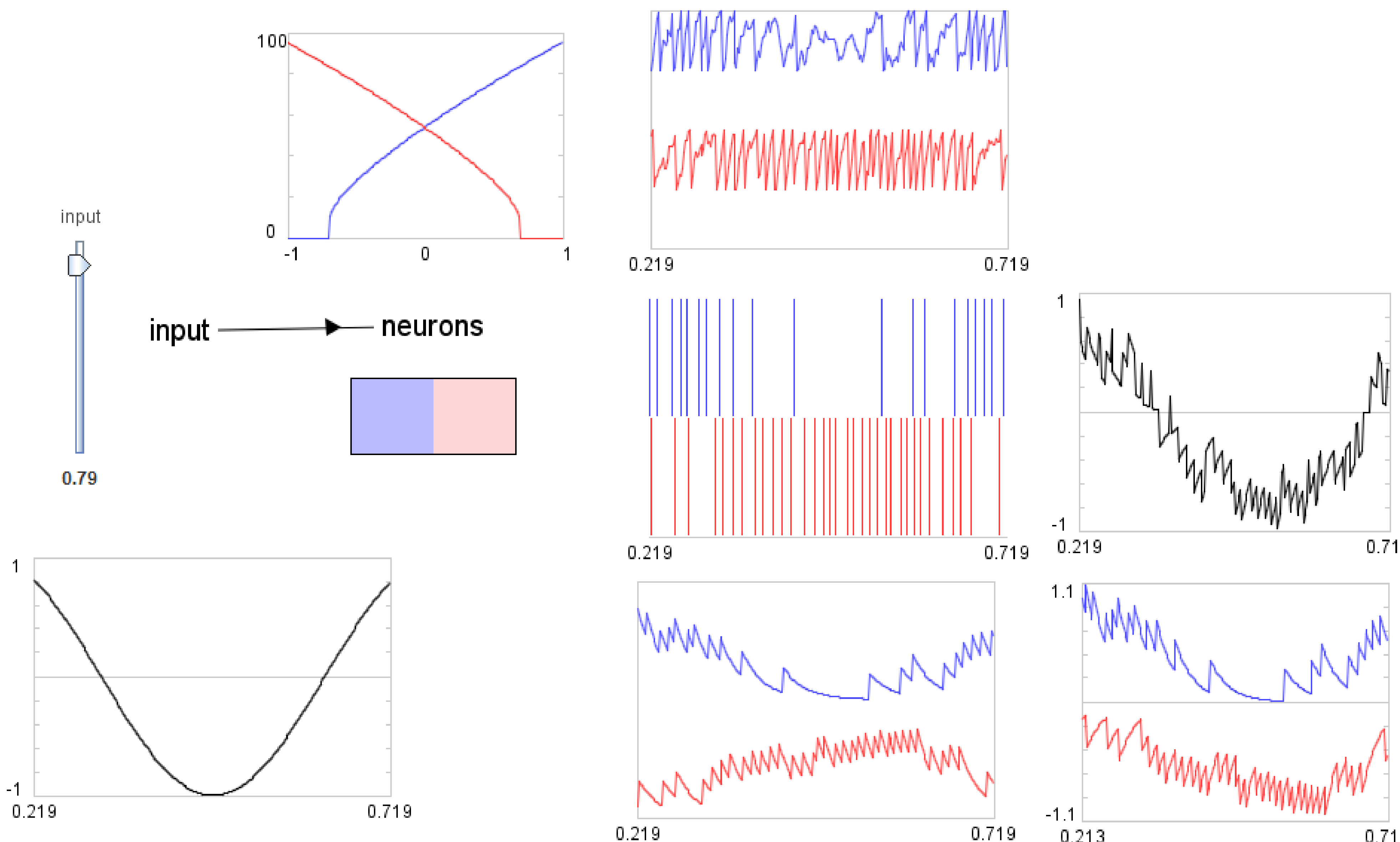
Spaun

- World's Largest Functional Brain Model
  - 2.5 million spiking neurons
  - 8 tasks, 1 eye, 1 arm, 20 brain areas
- Problems
  - Slow
    - (2.5 hours on high-end workstation for 1 second of simulation)
  - Power-hungry
    - (scaling up to 100 billion neurons would require a dedicated power station)
- Can neuromorphic hardware help?

Single Neuron

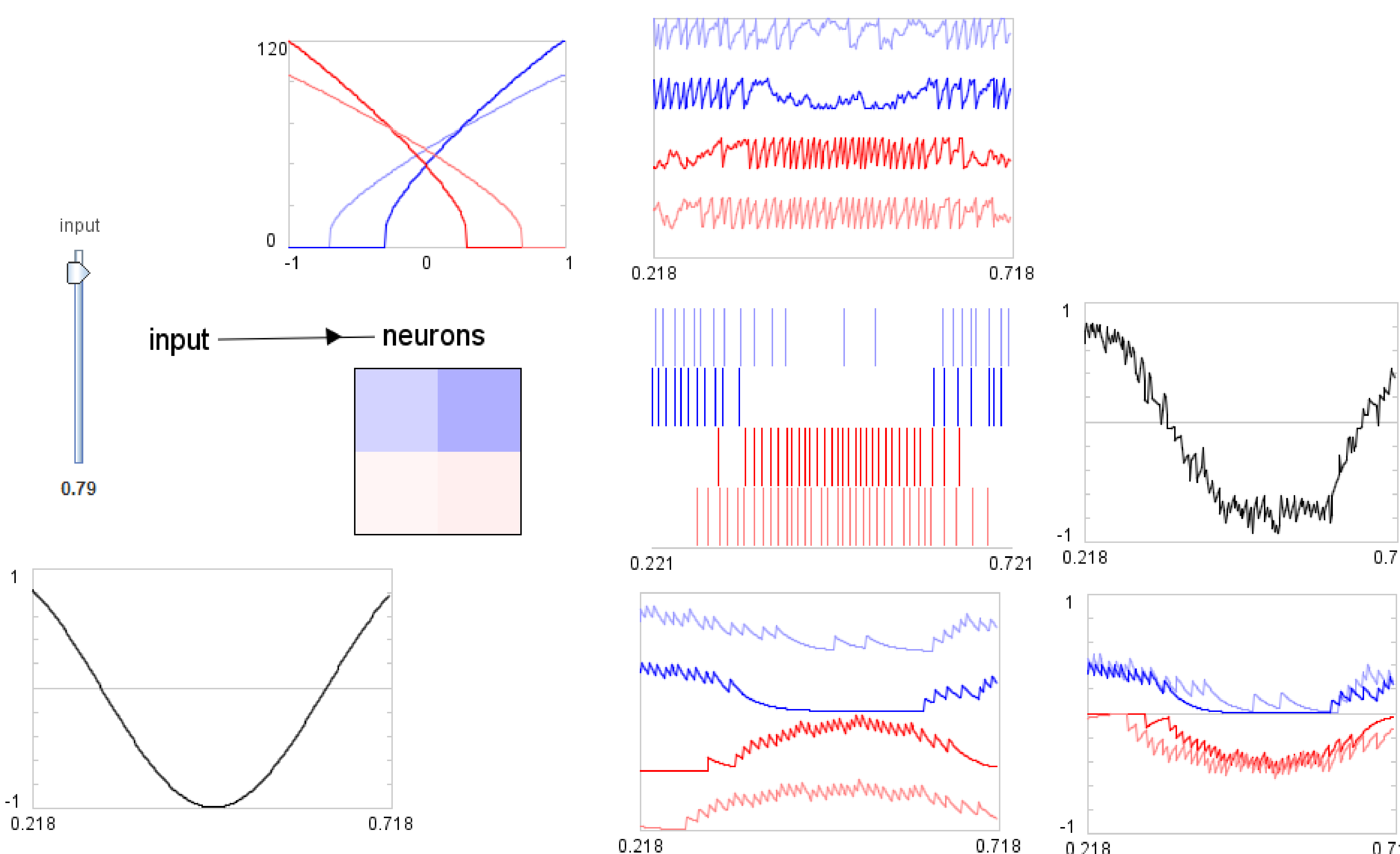


Two Neurons

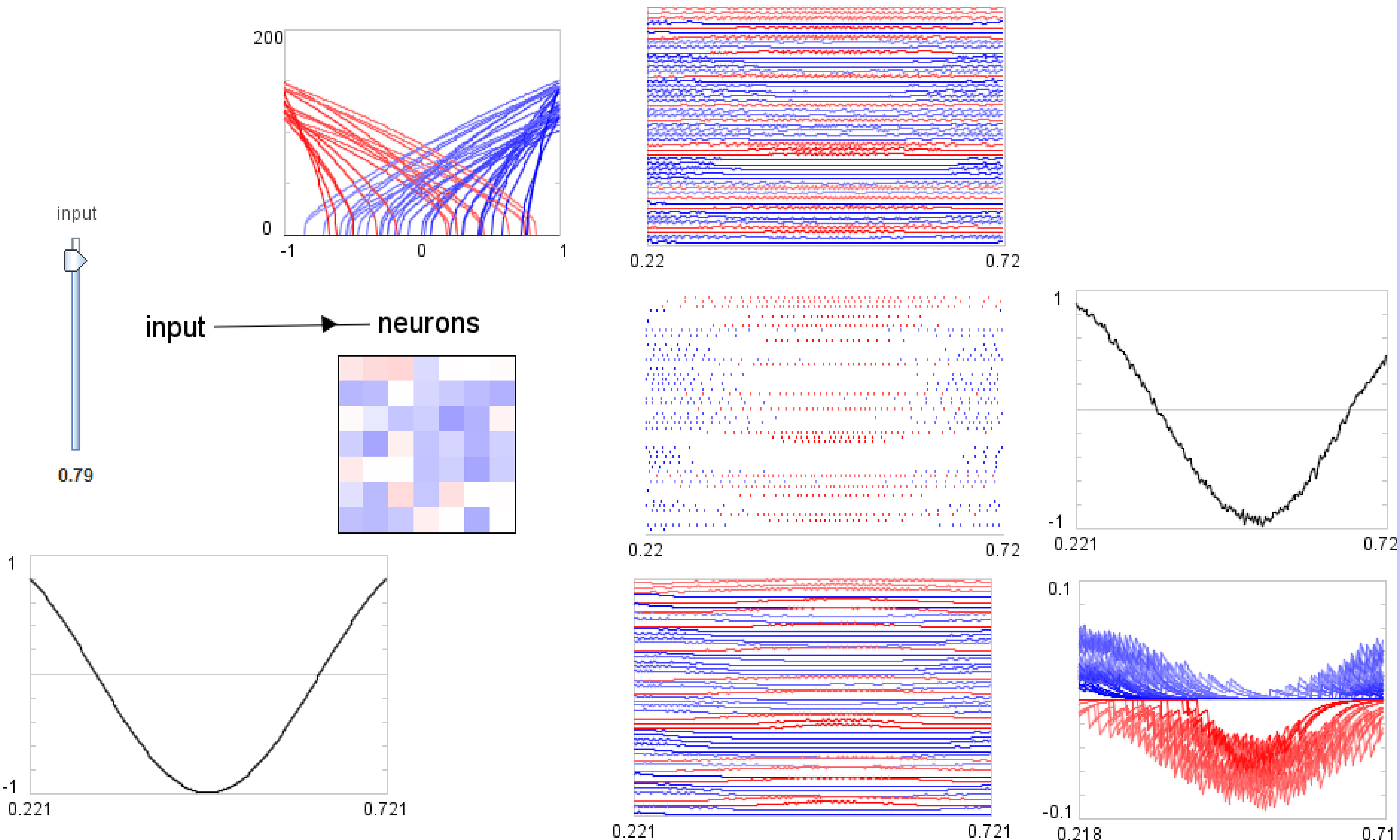


input
0.79
input
neurons
100
0
-1
0
1
0.219
0.719
1
-1
0.219
0.71
1.1
-1.1
0.213

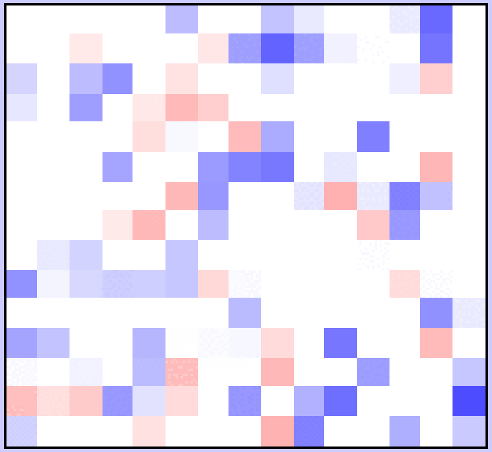
Four Neurons



Fifty Neurons

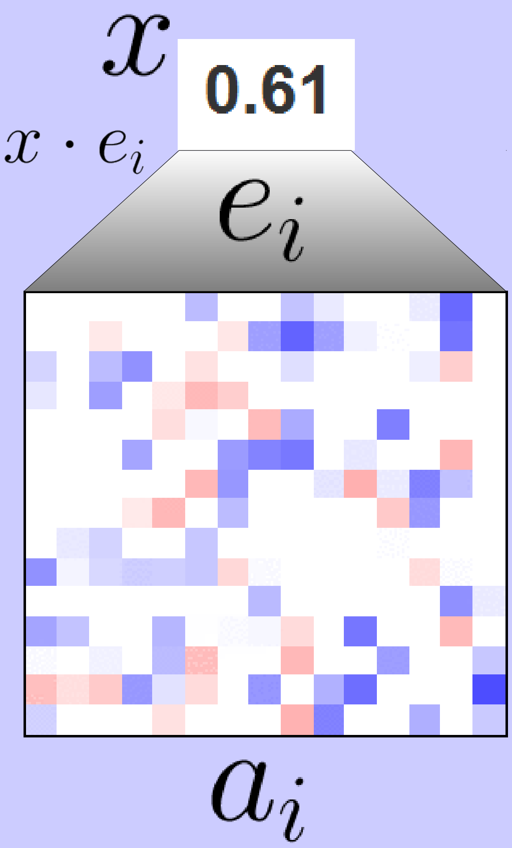


Communicating Between Pools



Communicating Between Pools

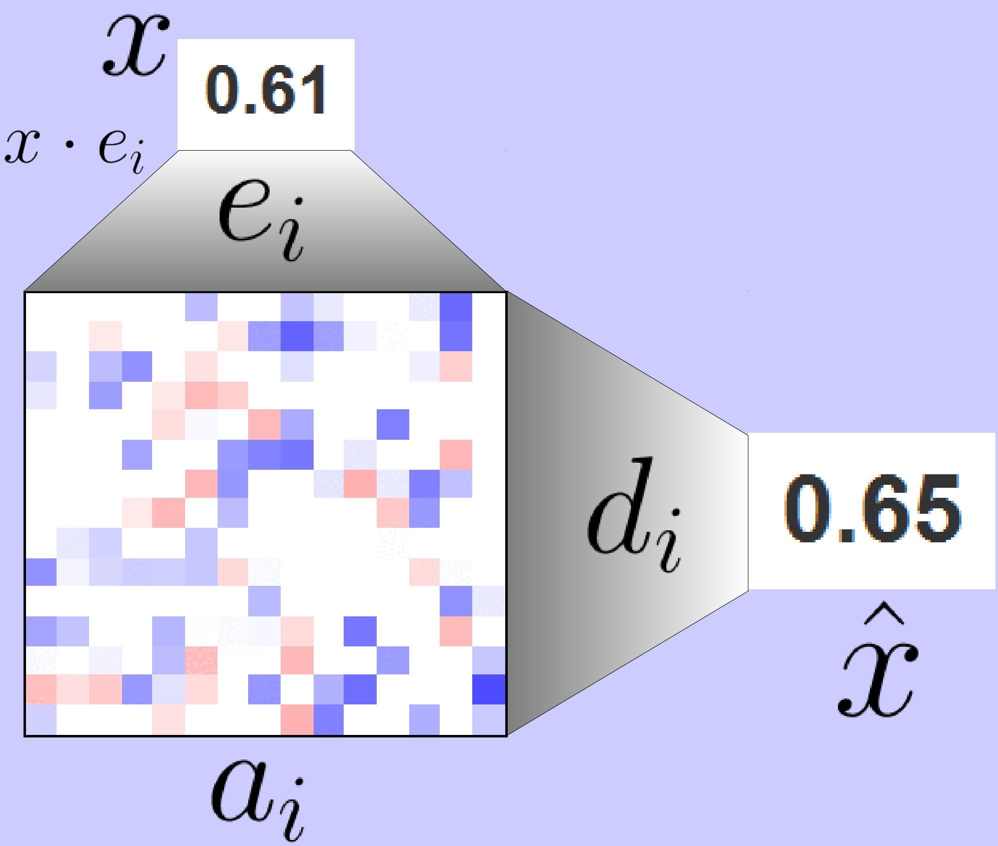
$J_i = x \cdot e_i$



$a_i = G_i[J_i]$

Communicating Between Pools

$J_i = x \cdot e_i$

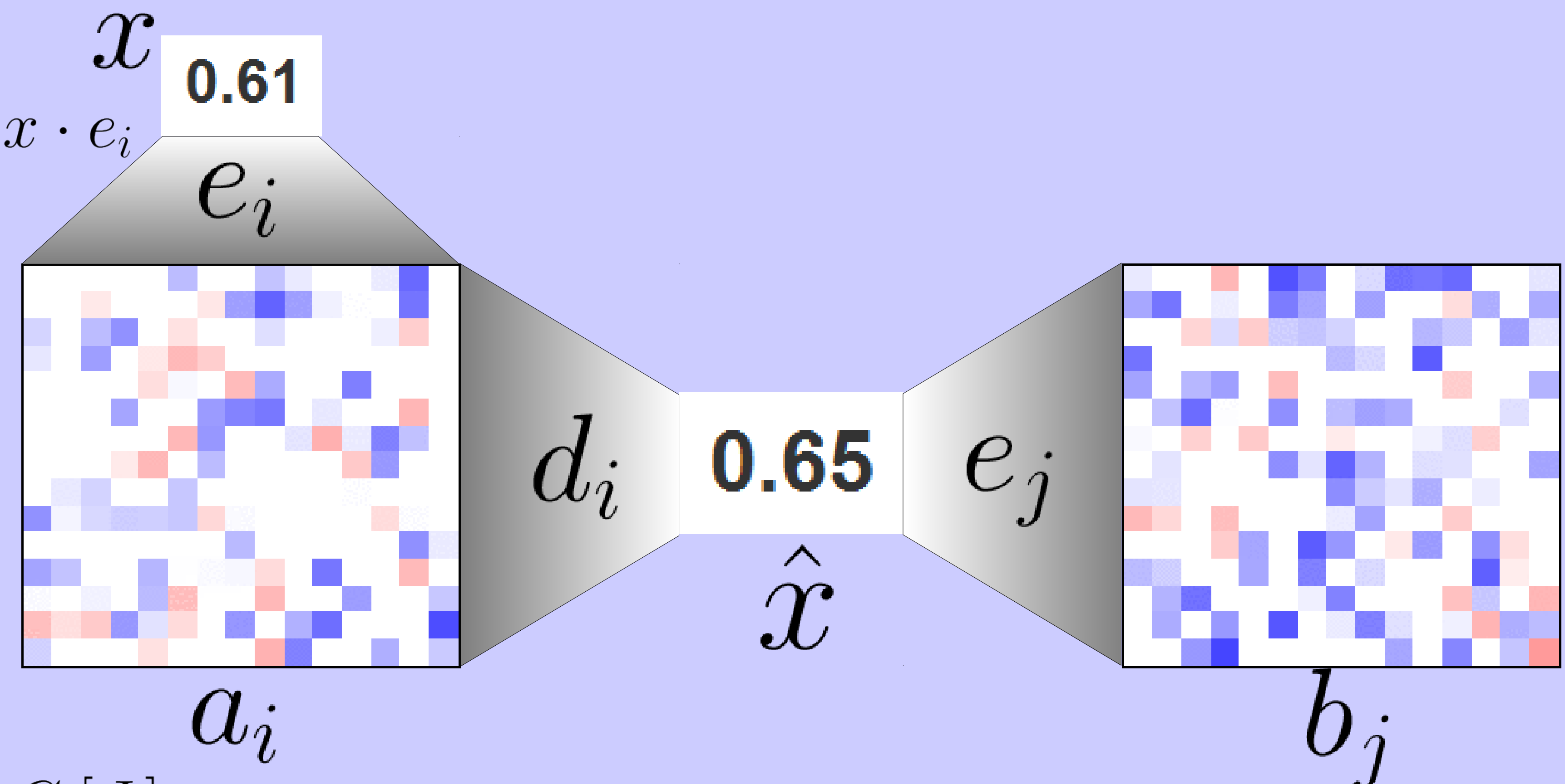


$a_i = G_i[J_i]$

$$\hat{x} = \sum_i a_i d_i$$

Communicating Between Pools

$J_i = x \cdot e_i$



$a_i = G_i[J_i]$

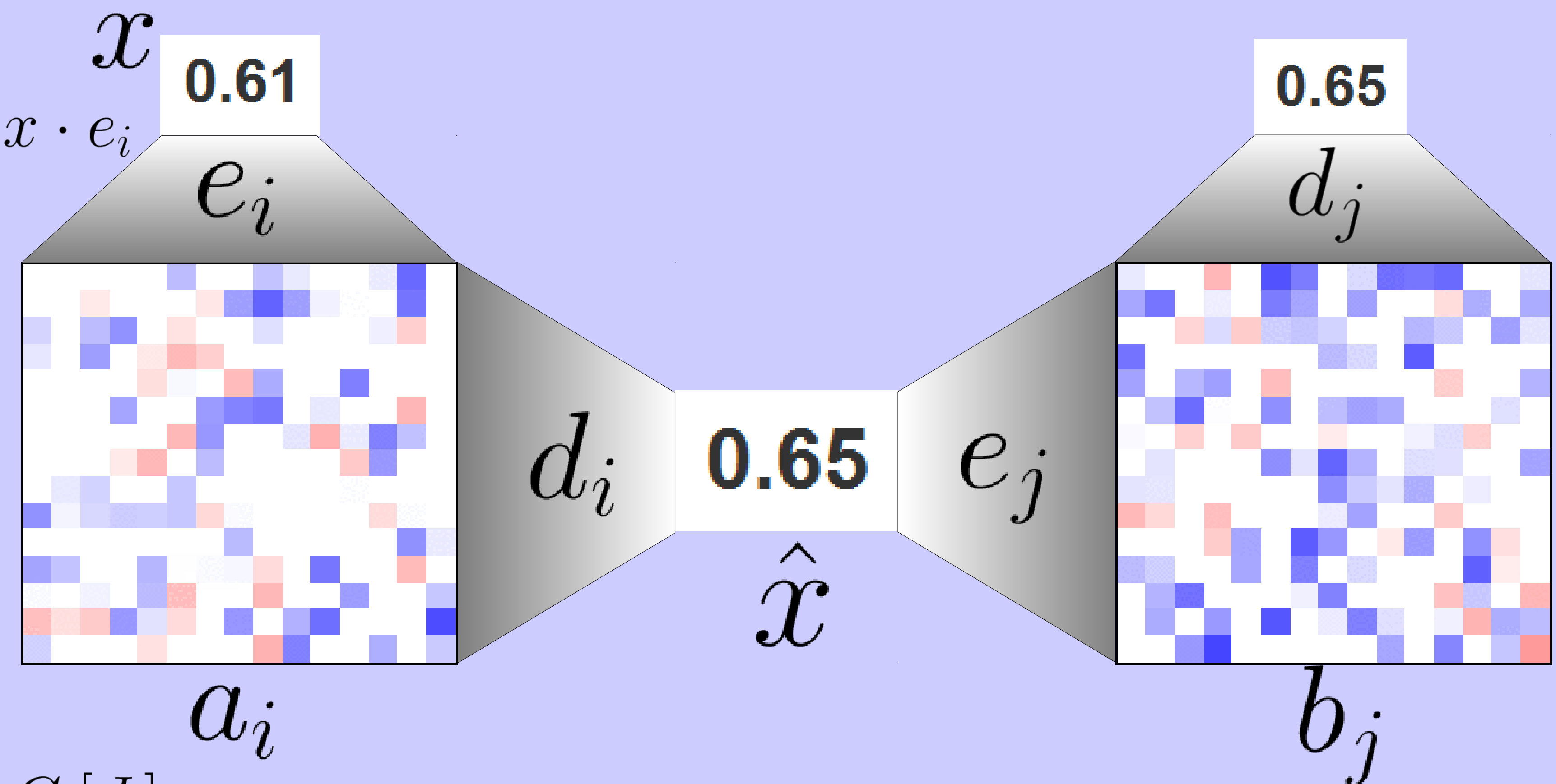
$b_j = G_j[J_j]$

$\hat{x} = \sum_i a_i d_i$

$J_j = \hat{x} \cdot e_j$

Communicating Between Pools

$J_i = x \cdot e_i$



$a_i = G_i[J_i]$

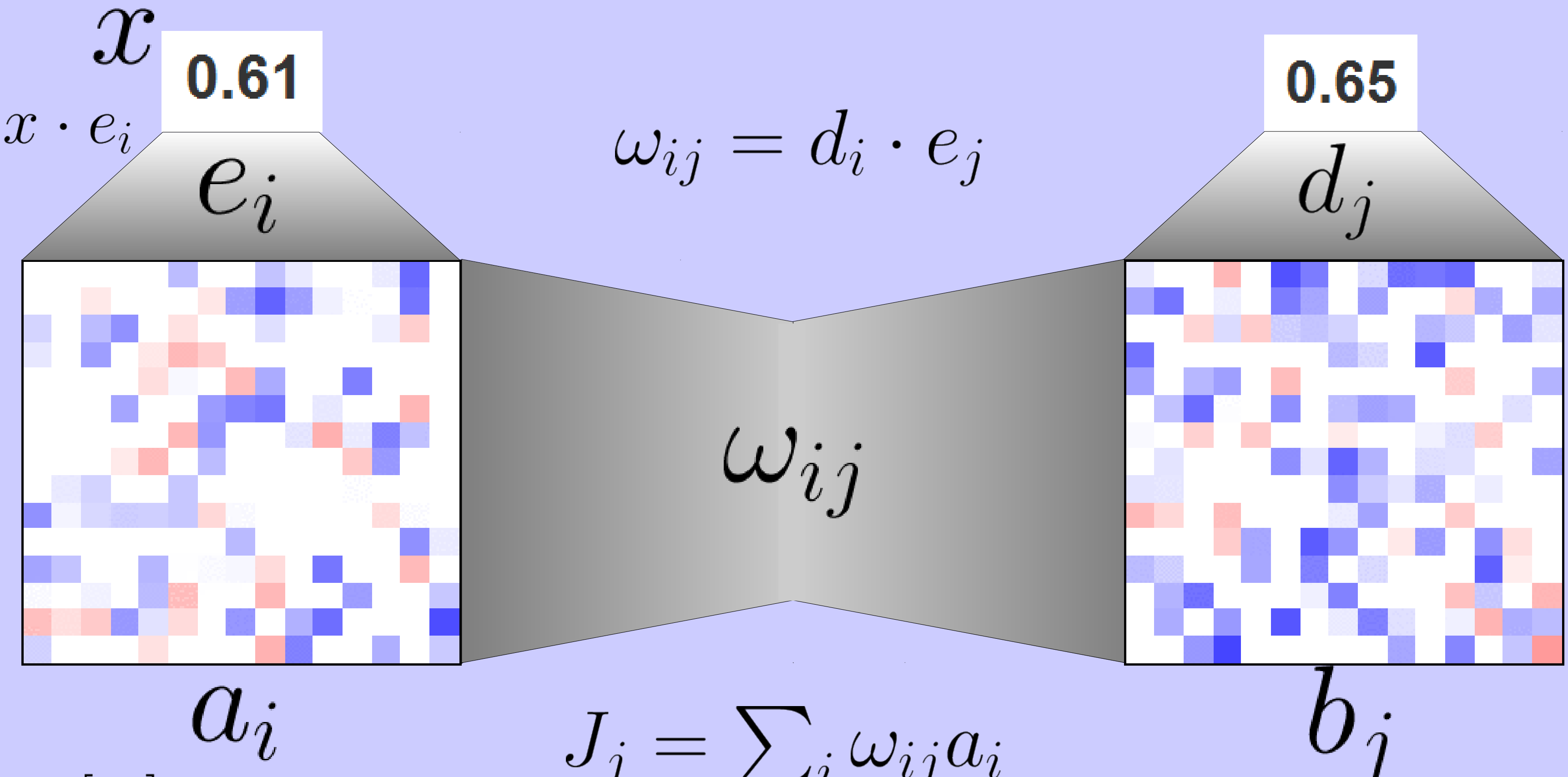
$b_j = G_j[J_j]$

$\hat{x} = \sum_i a_i d_i$ $\quad$ $J_j = \hat{x} \cdot e_j$

Communicating Between Pools

$J_i = x \cdot e_i$

$\omega_{ij} = d_i \cdot e_j$



$J_j = \sum_i \omega_{ij} a_i$

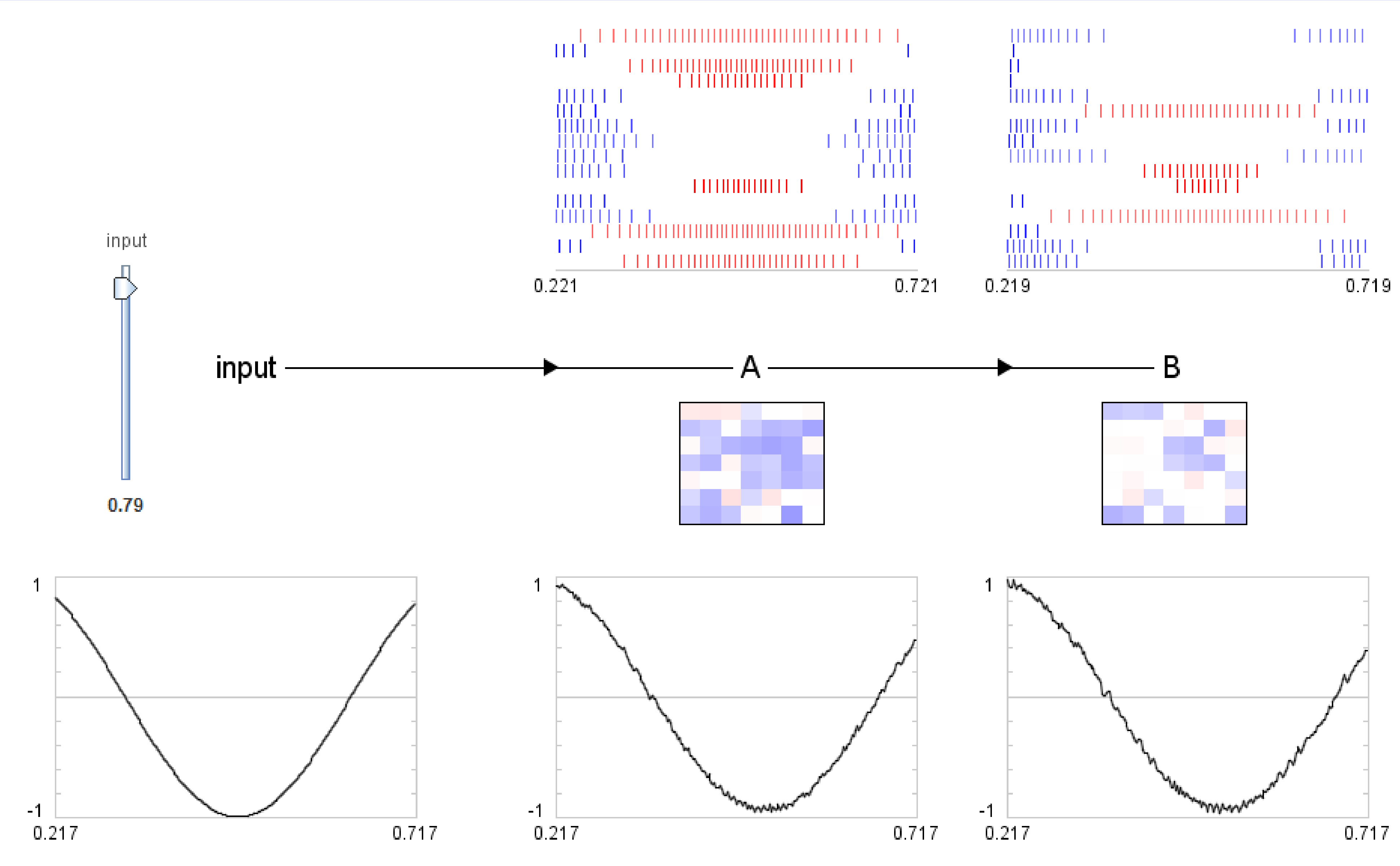
$a_i = G_i[J_i]$

$b_j = G_j[J_j]$

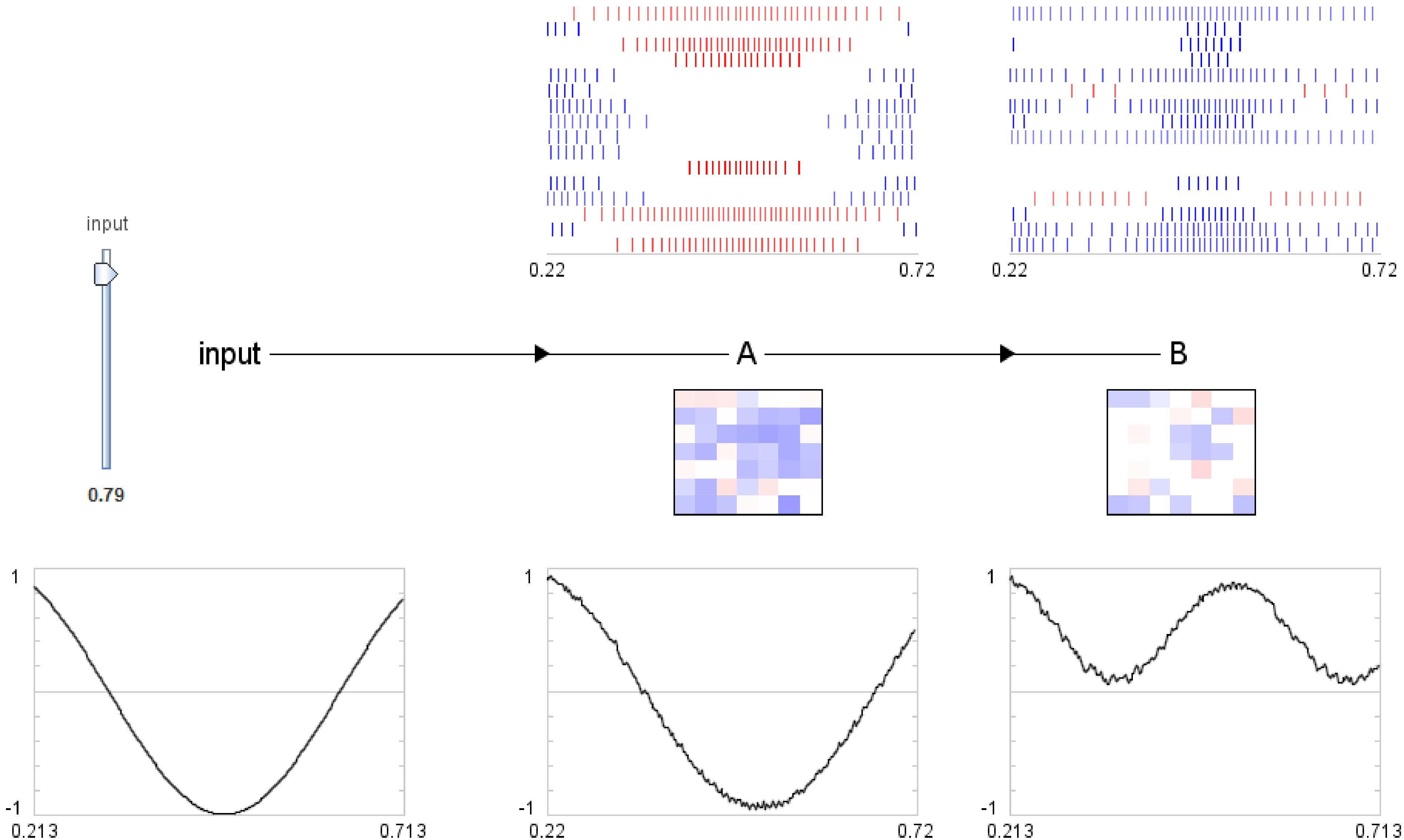
$\hat{x} = \sum_i a_i d_i$

$J_j = \hat{x} \cdot e_j$

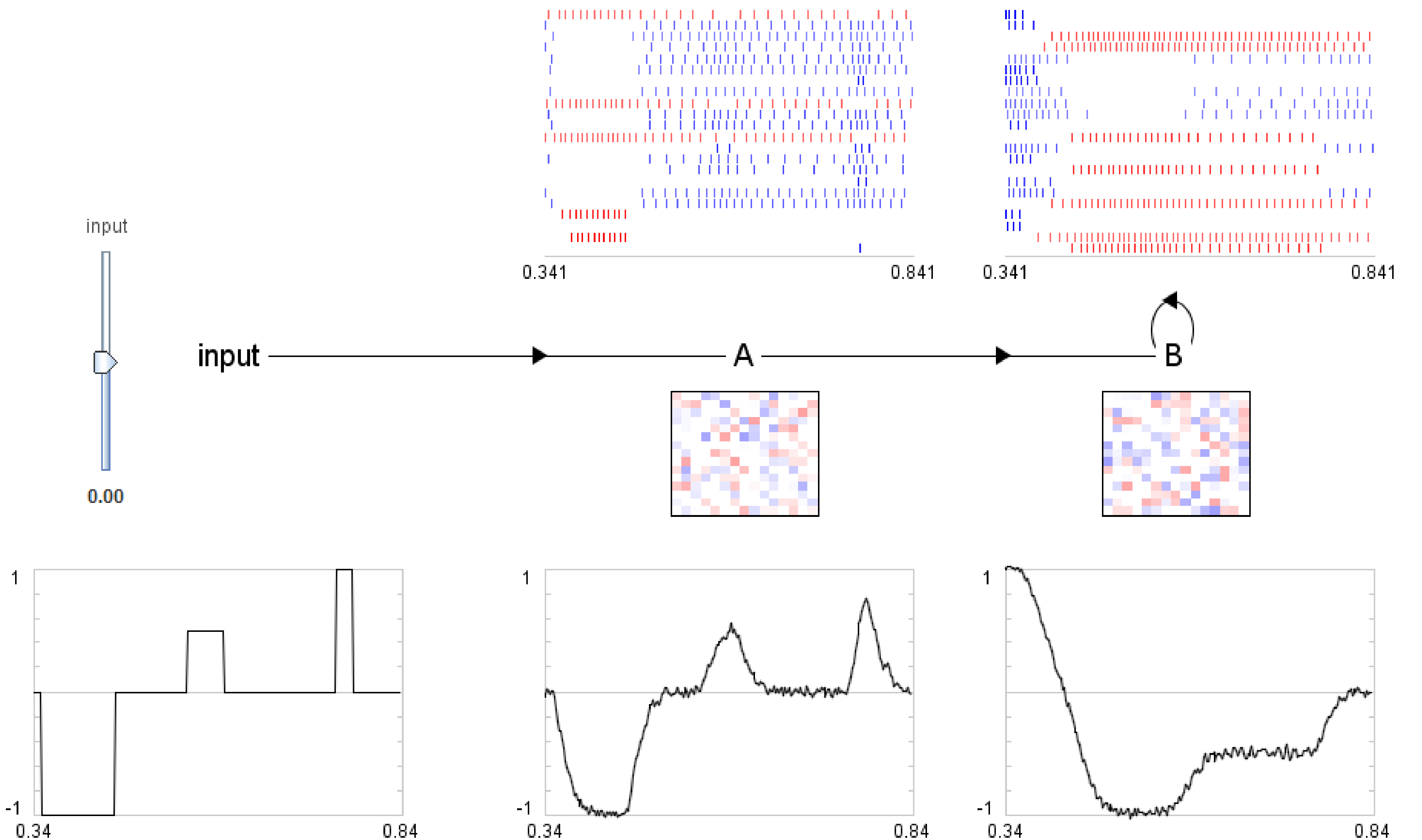
Communication Channel



Computation



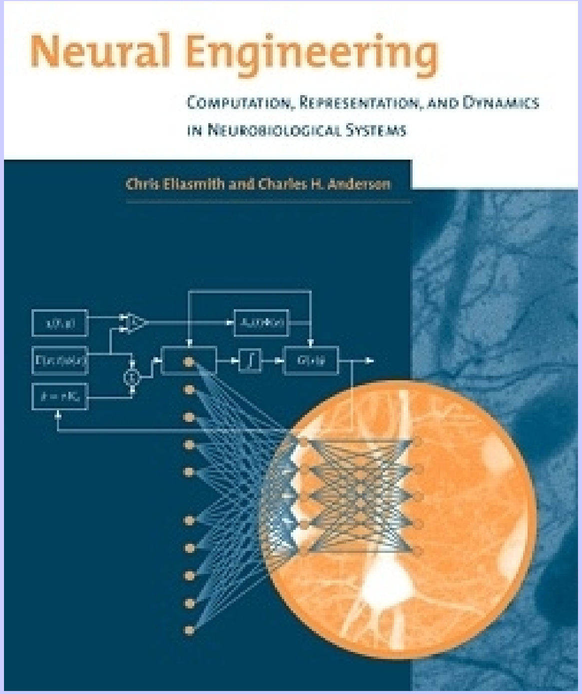
Memory



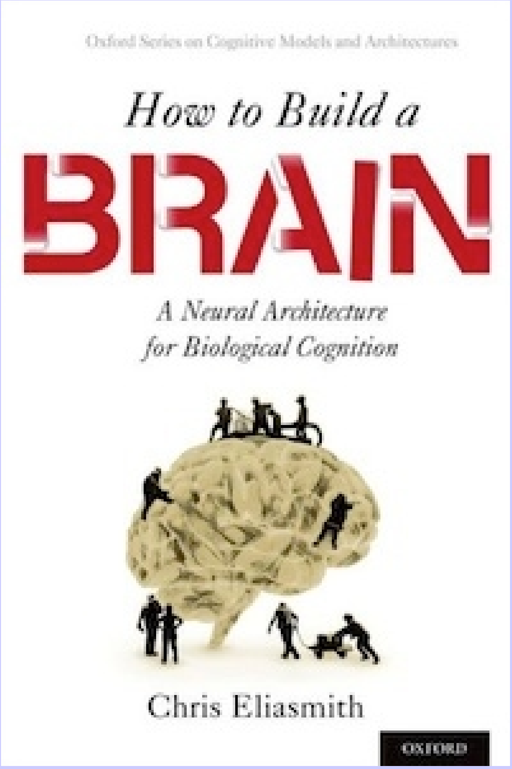
input
0.00
input
A
B
0.341
0.841
0.341
0.841
1
-1
0.34
0.84
1
-1
0.34
0.84
1
-1
0.34
0.84

Neural Engineering Framework

- Groups of neurons represent data
  - D-dimensional vectors (D<N)
  - Increasing N decreases error
- Connections compute functions
  - $y = f(x)$
  - More non-linear, less accurate
- Recurrent connections compute dynamics
  - $\dot{x} = f(x) + g(u)$
  - Need post-synaptic filter of $h(t) = Ae^{-t/\tau}$



Cognition



- Concepts are vectors
  - ~700 dimensional
- Memory is an integrator
- Concept combinations are vectors
  - ~700 dimensional
  - RED*CIRCLE + BLUE*SQUARE
  - SUBJECT*TOM + VERB*KNOWS + OBJECT*(SUBJ*DOGS + VERB*CHASE + OBJ*CATS)
  - * is circular convolution

Neuromorphic Hardware

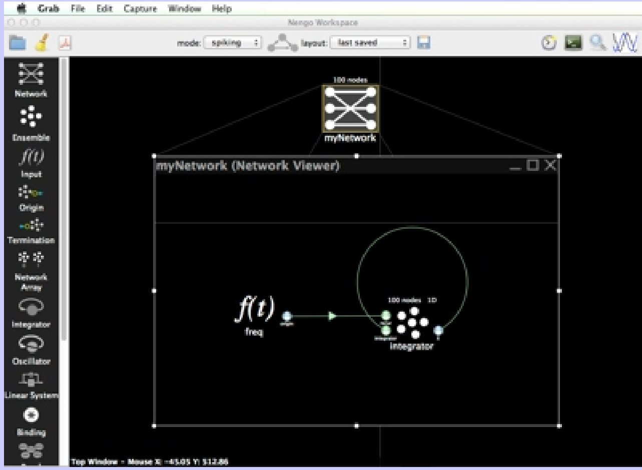
- Groups of Neurons
  - ~30 to ~60,000 neurons in a group
  - Any nonlinear neuron model
    - We use standard LIF
    - Customize neuron model based on what's most efficient in the implementation
  - Need to be heterogeneous
    - Varying gains, bias, etc
    - In analog hardware, transistor mismatch is a good thing!

Neuromorphic Hardware

- Connections between neurons
  - Need recurrent connections for memory, dynamics
  - By default, all-to-all
    - But very low-rank weight matricies
    - Weight matrix is factorable: NxN → NxD, DxN; D<<N
  - Can make weight matrix sparse
    - Lowers accuracy for nonlinear functions
  - Can use probability rather than weights
  - For cognition, need ~60,000 recurrent for memory
    - Need 60,000 → 700x200 → 60,000 for conceptual combination, extraction

Current Progress

- Nengo (http://nengo.ca)
  - Free, Open Source software for building models (including Spaun)
  - Tutorials, Demos, GUI, Scripting



- SpiNNaker
  - Export models from Nengo to SpiNNaker
- Neurogrid
  - Extending Nengo to deal with different types of connection constraints (e.g. input diffusers)
  - Starting 5-year project to develop new hardware

More Information

- Nengo (the software)
  - http://nengo.ca
- Spaun (the functional brain model)
  - Eliasmith et al. (2012). A large-scale model of the functioning brain. Science.
- NEF (the underlying theory)
  - Eliasmith & Anderson (2003). Neural Engineering
- SPA (the cognitive architecture)
  - Eliasmith (2013). How to build a brain