# Artificial astrocyte networks

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# Goal

- Use models and proof methods from artificial neural networks to try and set an upper bound on astrocyte computation.
- ANNs $\leftrightarrow$ AANs?

# ANNs

# What are ANNs?

- By example, using vision.
- Sparse networks.

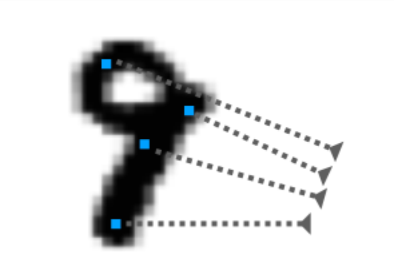
# Visual digit recognition.

= 1,2,3,4,5,6,...

# What are ANNs?

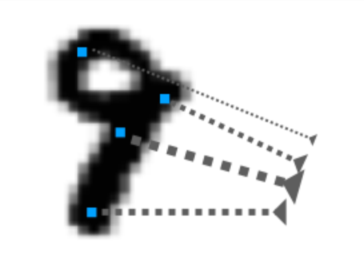
$= 9?$

# What are ANNs?



$$\sum X_{ij} = 9$$

# What are ANNs?



$$\sum w_{ij} x_{ij} = 9$$

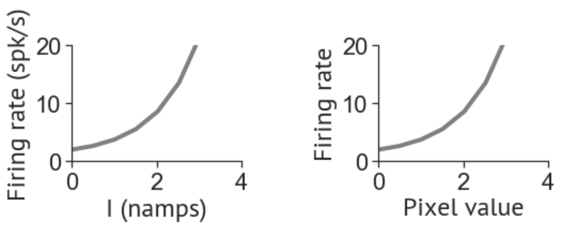
# What are ANNs?

$$\sum w_{ij}x_{ij} + b_i = 9$$

# What are ANNs?

$$\phi(\sum w_{ij}x_{ij} + b_i) = 9$$

# What are ANNs?




*FI*-curve (left) $\approx \phi$ nonlinearity (right)

# What are ANNs?


A deep ANN network. Each box is a *layer*: $\phi(\sum w_{ij}x_{ij} + b_i)$

# AANs

# Basic astrocyte limits.

- No synapses
- No axons
- No spikes

# Basic astrocyte limits.

- No spatial $\sum$
- No $w_i$

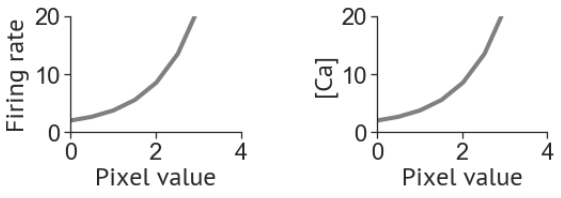
# Basic astrocyte properties

- $[Ca^{2+}]$ dynamics
- $[Ca^{2+}]$ dependent gliotransmission

# Recovering $\{\phi, w_i, \sum\}$?

- Let’s make three assumptions that let us form a functional analogy between neurons and astrocytes.

# Assumption 1 ($\phi$).




Firing rate (left) $\leftrightarrow$ $[Ca^{2+}]$ dynamics (right)

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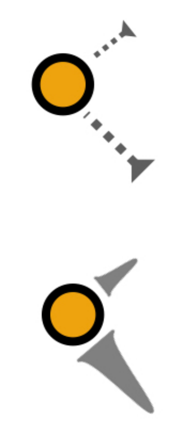
# Assumption 2 ($w_i$).

- Directional $[Ca^{2+}]$-dependent gliotransmission.



# Assumption 3 ($\sum$).

- Directional $[Ca^{2+}]$ waves, driven by gliotransmission.
    - Axons send spikes across a spatial distances with fidelity.
    - A $[Ca^{2+}]$ wave can travel a spatial distance with fidelity.

# In theory.

# Computational calcium waves.

- Let's treat neurons only as a source of input; glia do all the computation!
- Let's study a forward moving $[Ca^{2+}]$ wave.
- With Assumptions 1-3...
- Prove: it is a universal function approximator.

# A universal function approximator?

$F(x) - f(x)$

# A universal function approximator?

$F(x) - f(x)$

$F(x)$ : any target function (whose domain is bounded)

# A universal function approximator?

$F(x) - f(x)$

$F(x)$ : visual recognition system in cat (target)

# A universal function approximator?

$F(x) - f(x)$

$F(x)$ : visual recognition system in cat (*target*)

$f(x)$ : an ANN (*approximator*)

# A universal function approximator?

$$|F(x) - f(x)| < \epsilon$$

$F(x)$ : visual recognition system in cat (*target*)

$f(x)$ : an ANN (*approximator*)

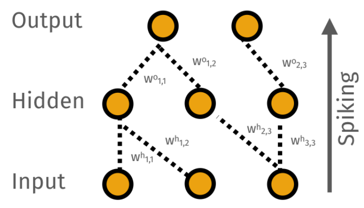
$\epsilon$ : the max error boundary

# A universal function approximator?

$|F(x) - f(x)| < \epsilon$

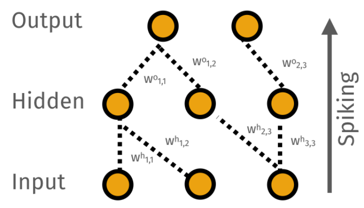
It is possible the target $F$ and learned function $f$ can be made arbitrarily close to $\epsilon$.

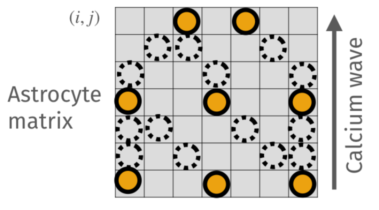
# Proof sketch.




- Bölcskei *et al* (2019) $F$ can be approximated by $f$ in $M << N$ connections.
- $f : \phi(\sum w_{ij}x_{ij} + b_i)$

# Proof sketch.



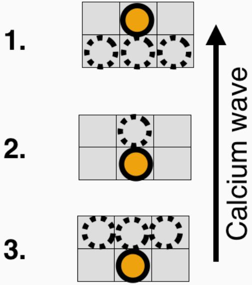

- Bölcskei *et al* (2019) $F$ can be approximated by $f$ in $M << N$ connections.
- $f : \phi(\sum^M w_{ij} x_{ij} + b_i)$

- Approximation of the universal approximator
- $w^o_{1,1} = \sum w^o_{i,j}$
- Astrocyte Sudoku

# In practice.

# Three astrocyte layers.

- In PyTorch I implemented three kinds of astrocyte layers.
- Using only nearest neighbor connections.
    1. Gather
    2. Slide
    3. Spread



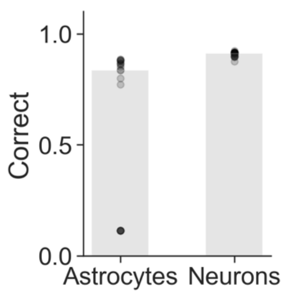
# An astrocyte network.

- Two equivilant neural (*left*) and astrocyte networks (*right*).
- For astrocyte computation width requires depth.

# Methods.

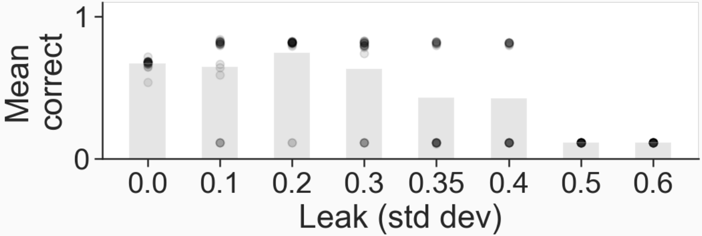
- Task: MINST digits
- Use: $\{slide, spread, gather\}$ in pytorch
    1. VAE, $N = (784, 20)$
    2. Perceptron, $N = (20, 30, 10)$
- Loss: Cross-entropy
- Optimizer: ADAM

# Results.




Test set performance (N=20 epochs)

# Results.




Effect of gliotransmitter diffusion on model performance

# Conclusions.

# Conclusions.

- AANs $\rightarrow$ universal function approximator.
- An upper bound for the performance of real astrocytes?
- AANs can solve hard vision problems.

# Future work.

- Upper bound $\rightarrow$ biological upper bound (help)
- Recurrent waves (in collaboration)
- Better motivated tasks (help)

# Open science.

Code `github.com/CoAxLab/glia_playing_atari`

Talk `github.com/parenthetical-e/glia-talk-sfn-2019`

Thank you!