Artificial Kuramoto Oscillatory Neurons (AKOrN)

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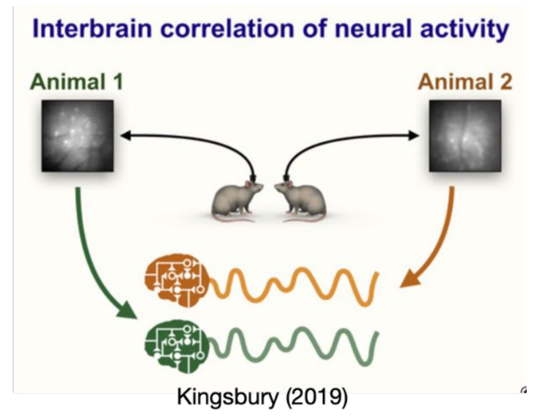
Synchronization occurs everywhere around us...

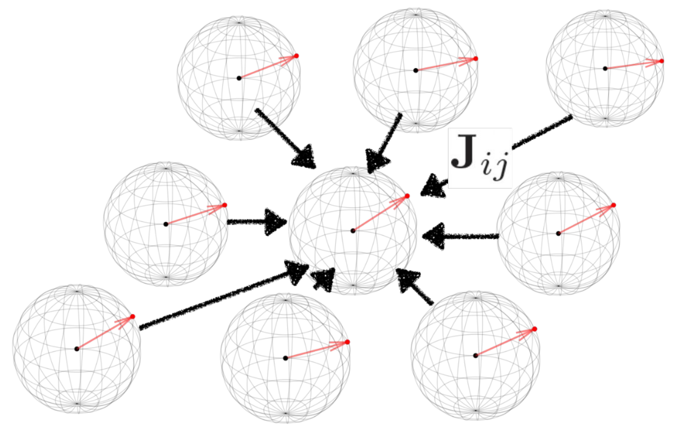
Synchronization is ubiquitous in nature and is a key mechanism for information processing in the brain. A famous model is called the **Kuramoto model (1975),** which is a simple dynamical model that describes the synchronization of oscillators. We incorporate **a generalized version of the Kuramoto model** into the neuronal dynamics.

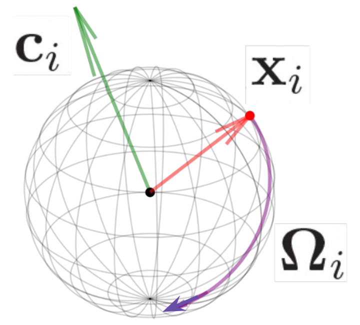


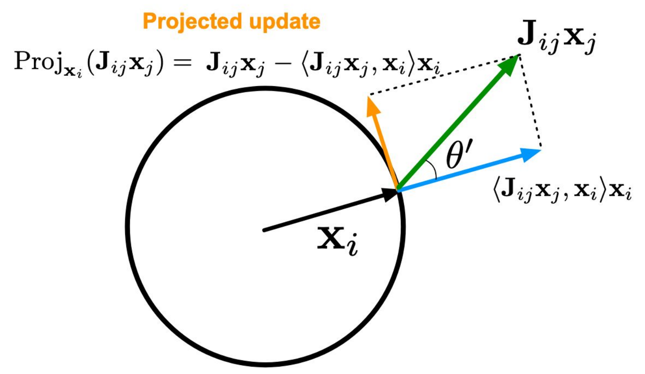



AKOrN

Essence of AKOrN: Multi-dimensional oscillators evolving dynamically on **hyperspheres**



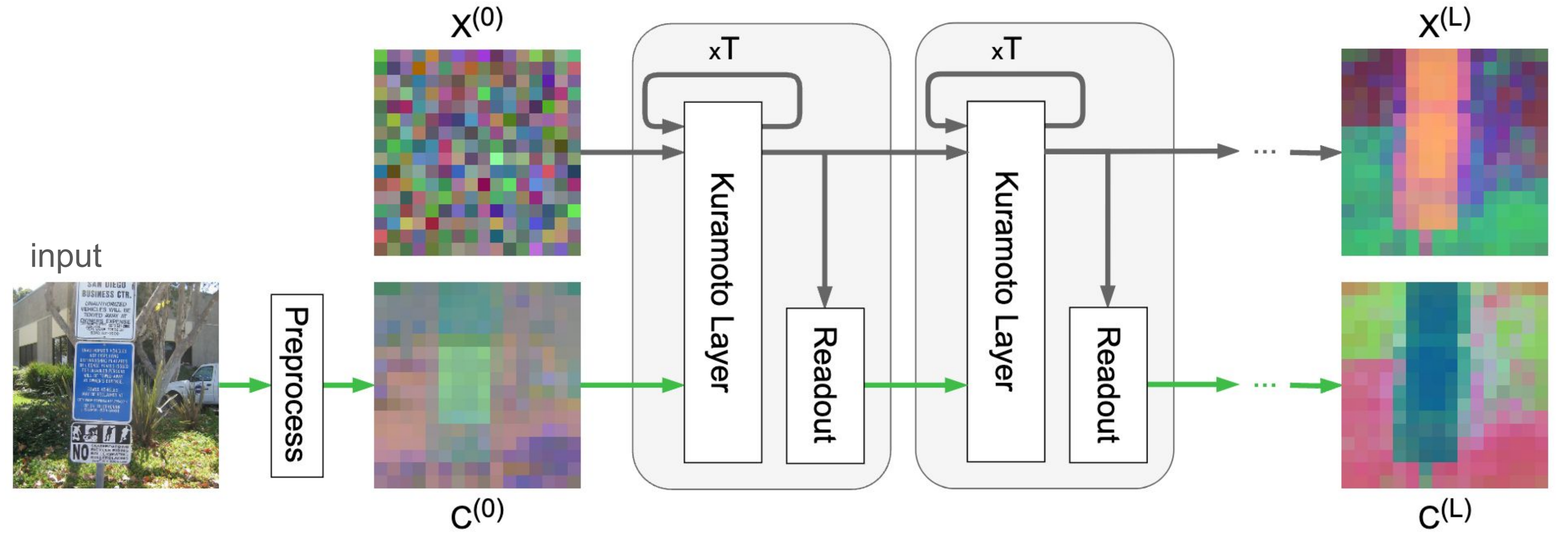




AKOrN dynamics:

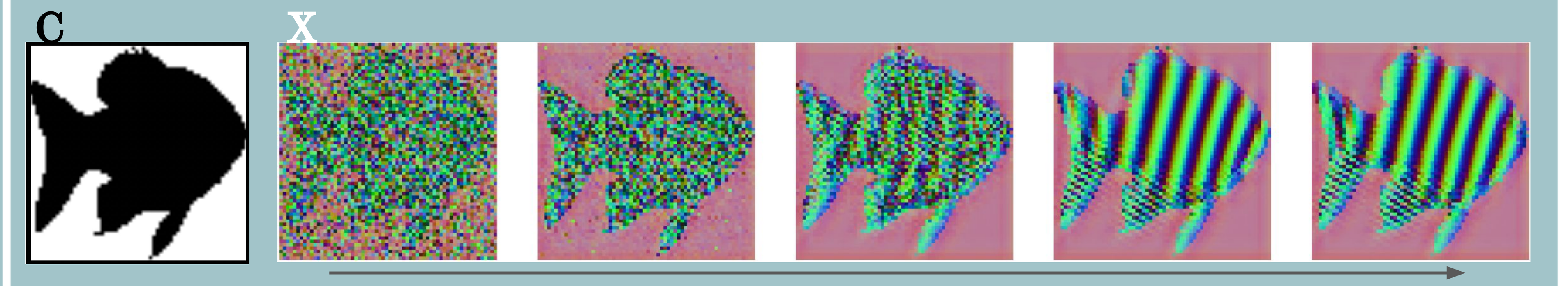
$$\dot{\mathbf{x}}_i = \Omega_i \mathbf{x}_i + \mathrm{Proj}_{\mathbf{x}_i}(\mathbf{c}_i + \sum_j \mathbf{J}_{ij}\mathbf{x}_j) \text{ where } \mathrm{Proj}_{\mathbf{x}_i}(\mathbf{y}_i) = \mathbf{y}_i - \langle \mathbf{y}_i, \mathbf{x}_i \rangle \mathbf{x}_i$$

AKOrN-based networks



1. **Create initial C and X**
   - Process the input to make the initial conditional signal $\mathbf{C}^{(0)}$
   - Initialize oscillators $\mathbf{X}^{(0)}$ by sampling from uniform distribution on the sphere.
2. **Update oscillators**
   - Update oscillators by the dynamics of AKOrN
     - Iterate T times and obtain **X**(l, T)
   - The Readout module creates new conditional signal $\mathbf{C}^{(l)}$ from **X**(l, T)
   - $\mathbf{X}^{(l)}$:= **X**(l, T) is passed to the next layer
   - Stack multiple [Kuramoto layer + Readout] modules
3. **Convert the final states to task representations**
   - The final $\mathbf{C}^{(L)}$ is used to make the final prediction for the task
     - E.g.: For image classification, $\mathbf{C}^{(L)}$ is further processed by (pooling+) the softmax classifier.

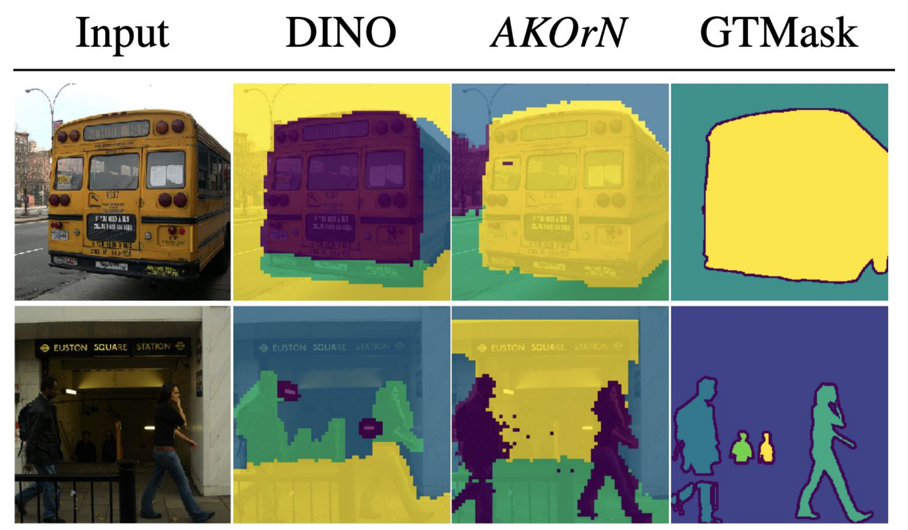
Synchronization dynamics bind features, enable better reasoning, and yield robust predictions in deep neural networks.

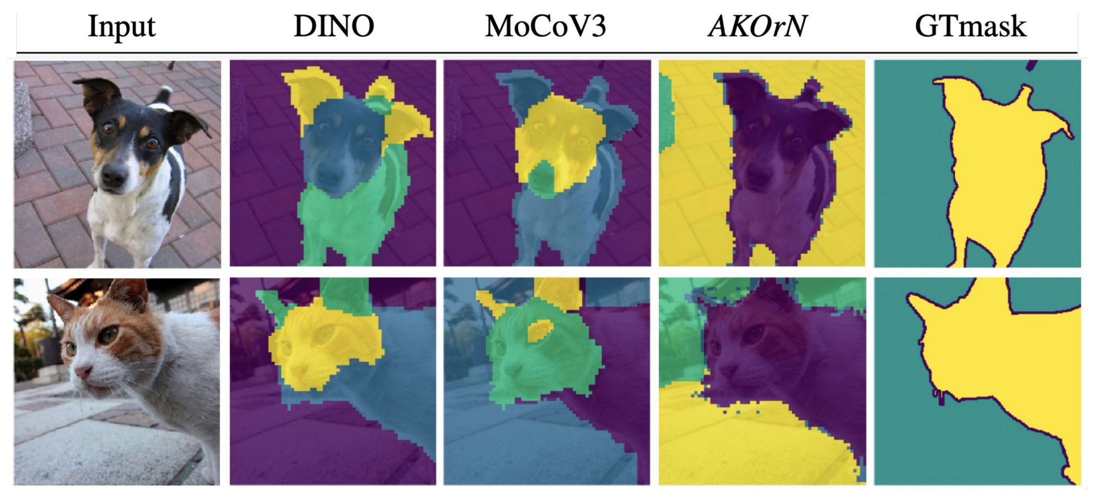


Project page

Binding features on natural images

Among well-known self-supervised learning models, AKOrN's features align best with objects in the scene.



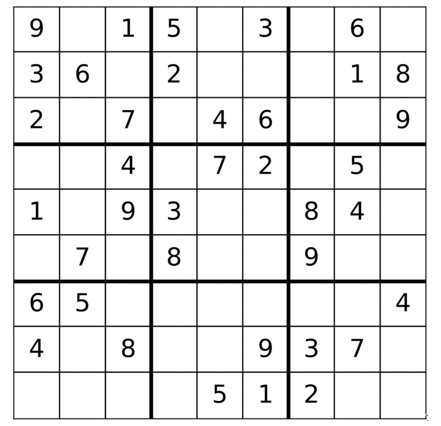


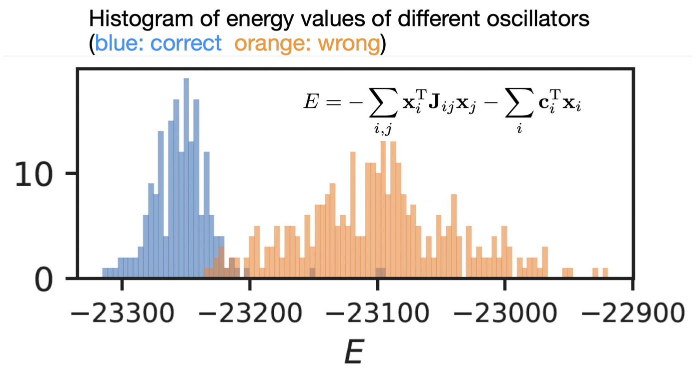
Visualizing clustered features of self-supervised learning models.
Models are trained on ImageNet in a self-supervised manner (SimCLR)

Better reasoning with test-time inference

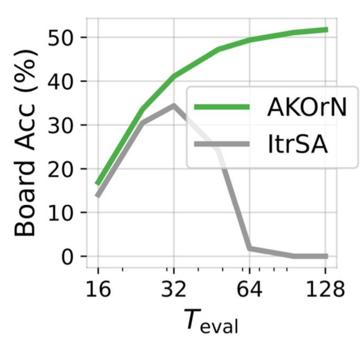
The Kuramoto layer behaves like an energy-based model, enabling two ways to perform test-time inference.

Task: fill blanks so that vertical, horizontal lines, and each 3x3 sub-block have all digits [1-9], Models are trained to classify the digits on blank squares.

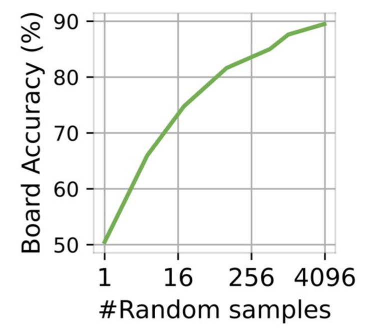


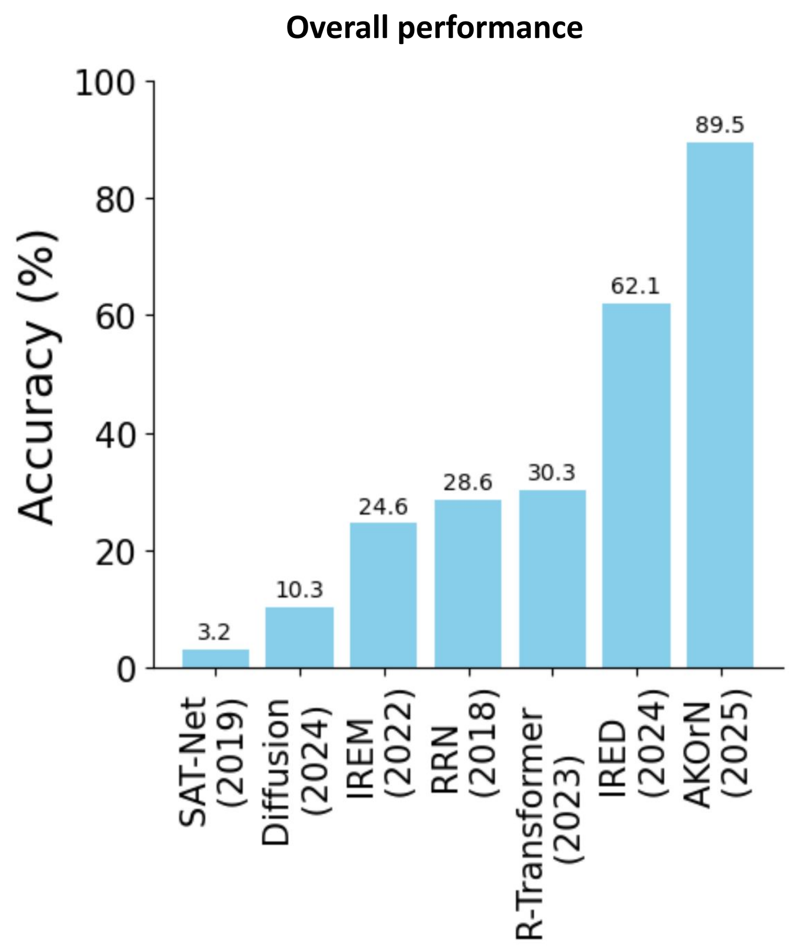


1. Test-time extension of Kuramoto updates



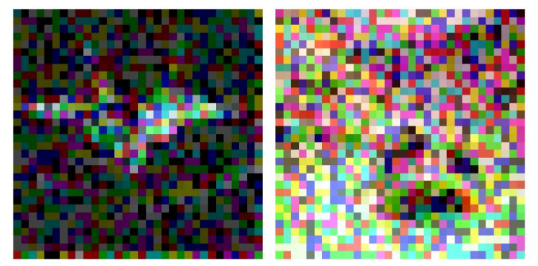
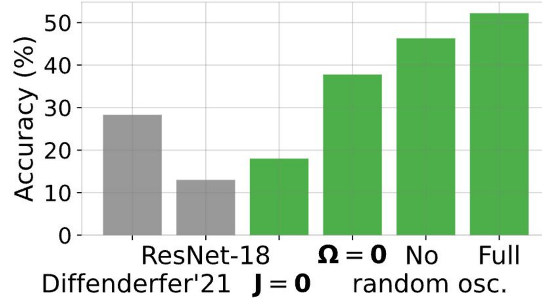
2. Energy-based voting

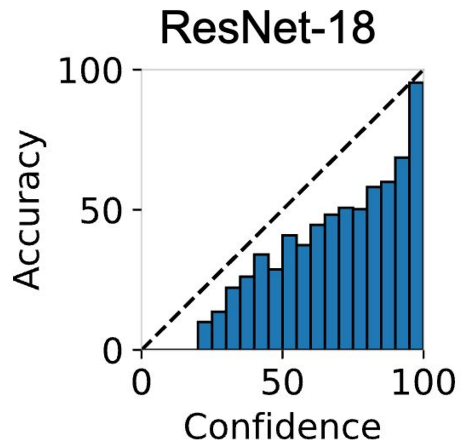


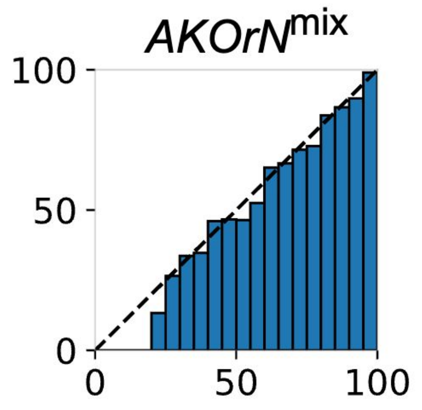


Robust and calibrated predictions

AKOrN-based networks are robust to random and natural perturbations, with calibrated predictions.





Models are trained on CIFAR-10 image classification tasks and are evaluated randomly/naturally perturbed images