SPICE workshop
Mainz 2018

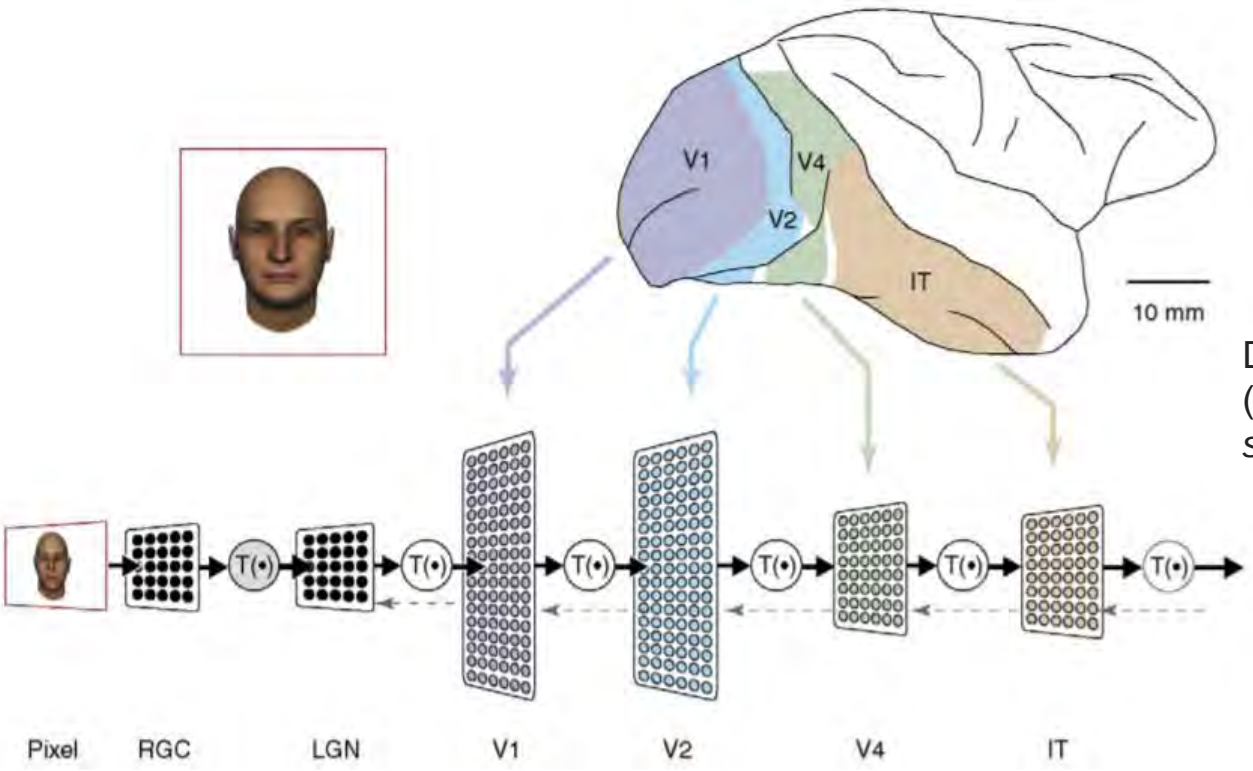
Bioinspired Computing Leveraging the Non-Linearity of Magnetic Nano-Oscillators

Damien Querlioz, D. Vodenicarevic, N. Locatelli, T. Hirtzlin, M. Ernoult
C2N, Univ. Paris-Sud, CNRS, Orsay, France

Julie Grollier, M. Romera, P. Talatchian, F. A. Araujo, V. Cros, P. Bortolotti, J. Trastoy, M. Ernoult
UMP CNRS/Thales, Palaiseau, France

Shinji Yuasa, S. Tsunegi, A. Fukushima, K. Yakushiji, H. Kubota
AIST, Japan

Artificial Neural Networks Look Like the Brain, to Some Extent

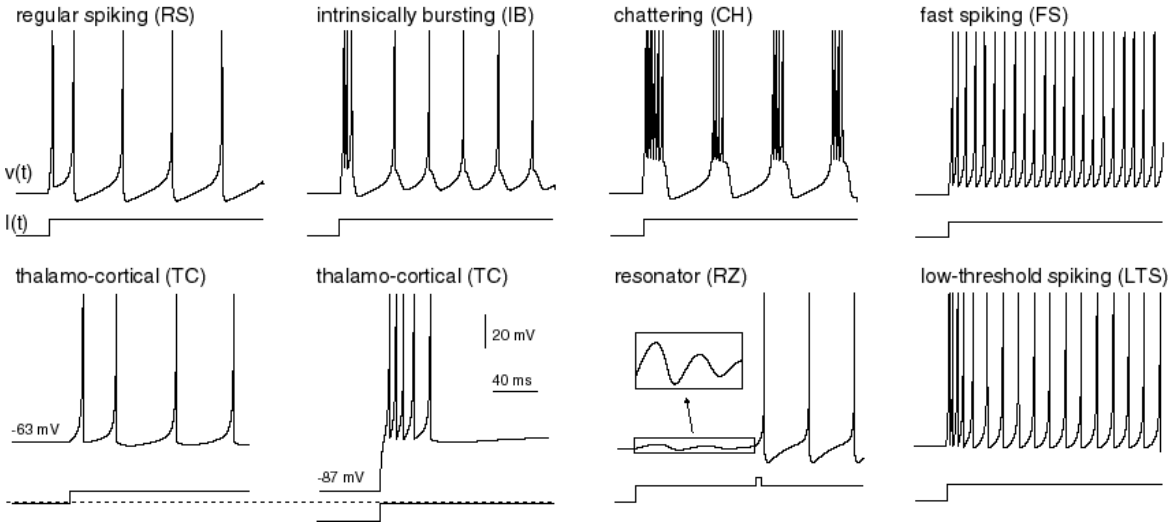


DiCarlo, J. J., & Cox, D. D. (2007). *Trends in cognitive sciences*, *11*(8)

But there are fundamental differences

What Is a Neuron?

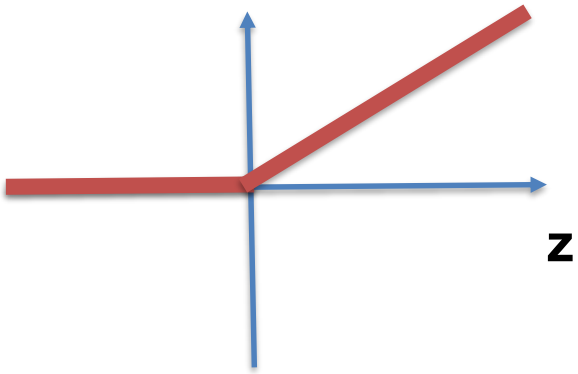
Brain neuron



Izhikevich, *IEEE TNNLS 2003*

ANN neuron

A=ReLU(z)



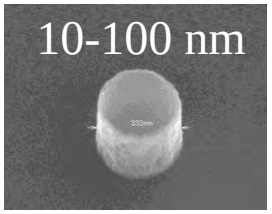
Non linearity is the only shared property
The simplification of neurons is actually a key of deep learning success

Are we missing an opportunity?

Non Linear Dynamical Devices Now Exist: Magnetic Nanooscillators

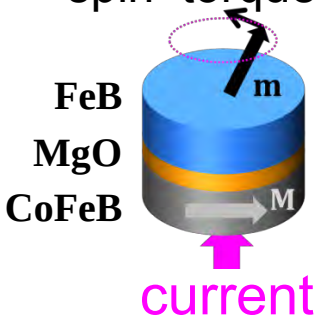
Nanoscale, fast (GHz), non-linear and easily measurable

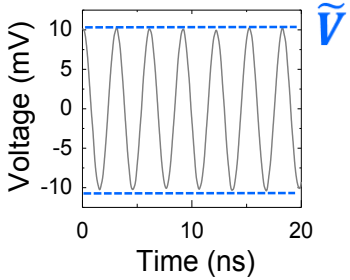
magnetic tunnel junction

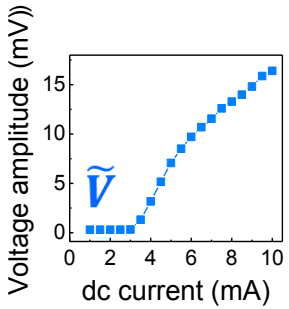


CMOS-compatible

spin torque



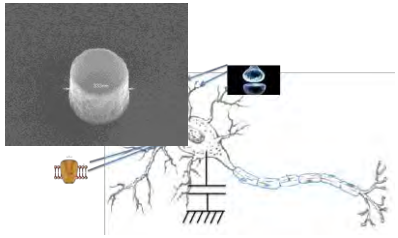




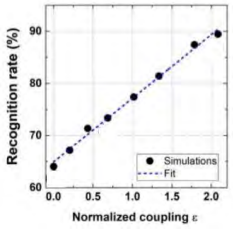
Same structure as magnetic memories

Can we use them as neurons?

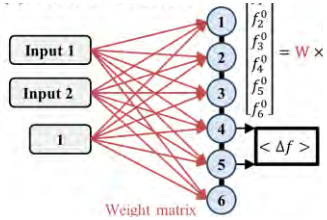
Bioinspired Computing Leveraging the Non-Linearity of Magnetic Nano-Oscillators



- Can We Use Coupled Dynamical Devices for Computation?



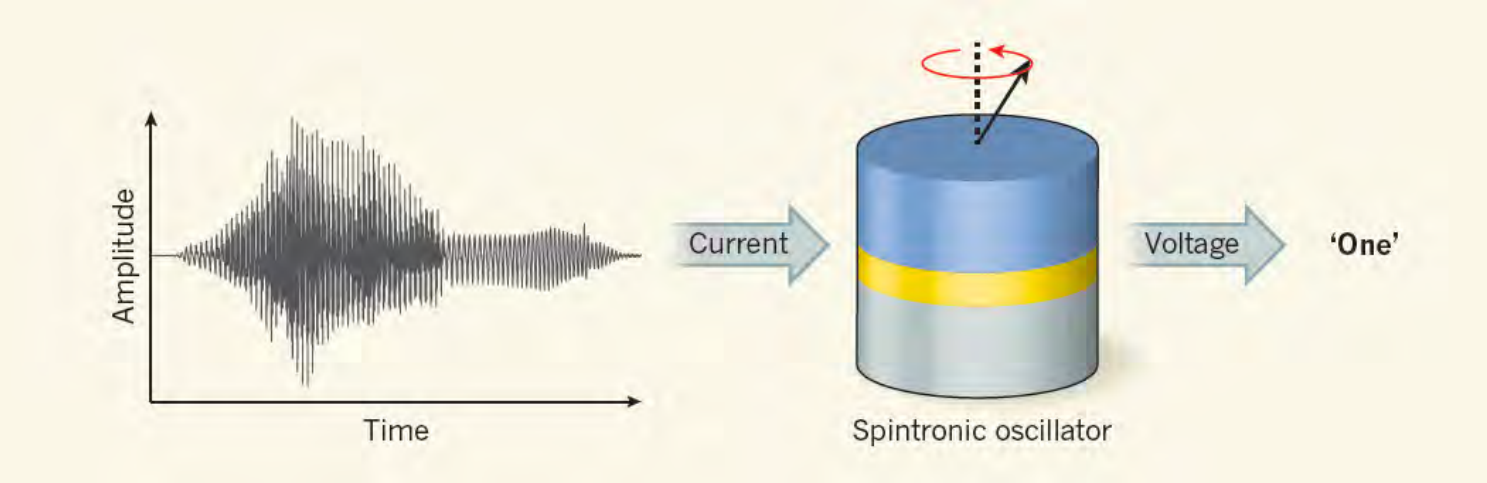
- Why Is It Working?



- Can We Use Concepts from AI with Nanooscillators?

First Idea: Use a Single Device to Implement an Assembly of Neurons

Mark D. Stiles talk

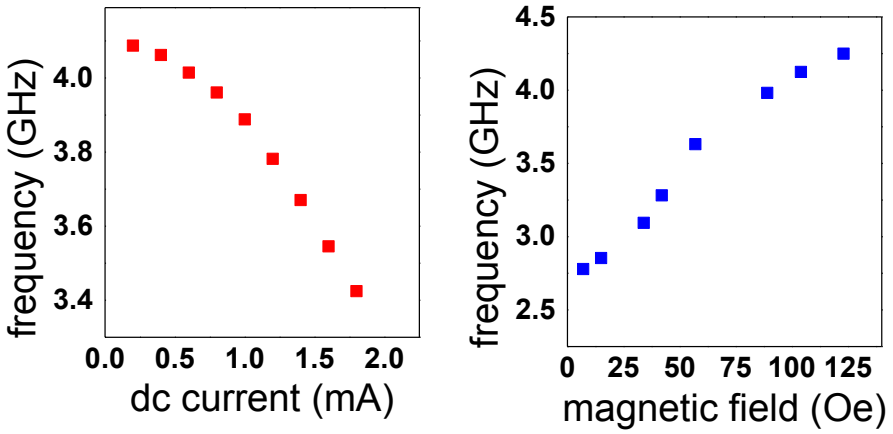


J. Torrejon, M. Riou, F. Abreu Araujo et al, Nature 547, 428 (2017)

Spoken digit recognition through reservoir computing
Exploiting STNOs' dynamics and non-linearity

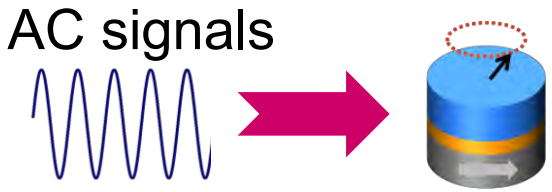
New Work: Exploiting the Whole Physics of Magnetic Nanooscillators

Tunability



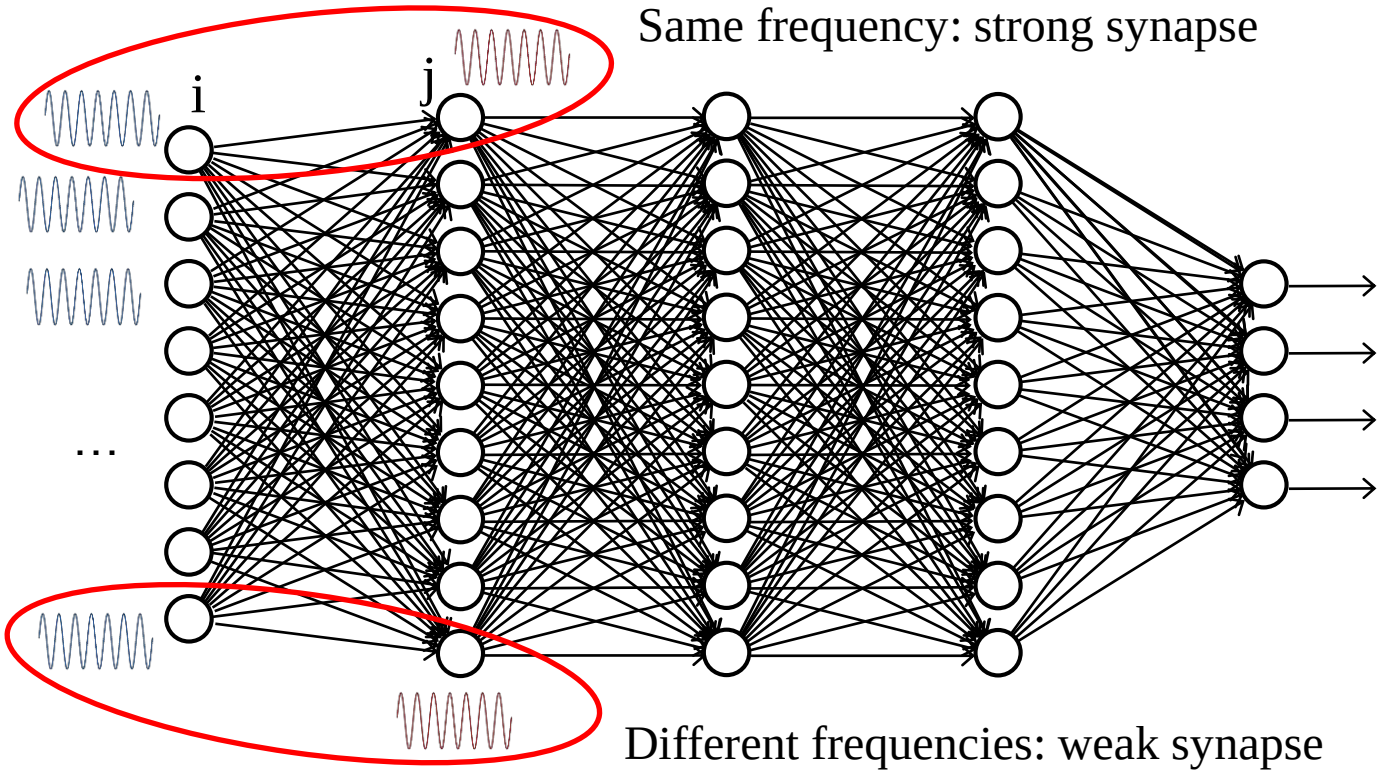
A. Slavin and V. Tiberkevich,
IEEE TM 45, 1875 (2009)

Ability to synchronize to AC signals



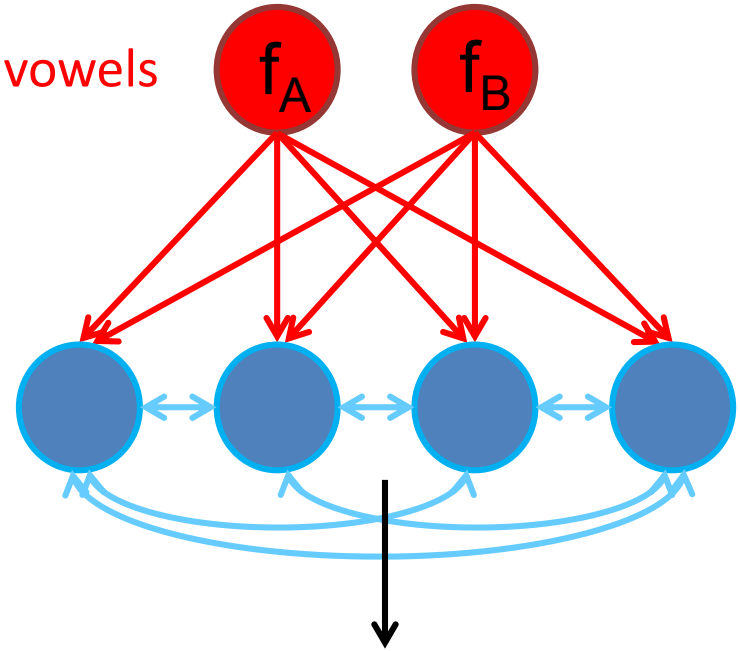
W. H. Rippard et al., PRL. 95, 067203 (2005)
R. Lebrun, **JG** et al, PRL 115, 017201 (2015)
A. A. Awad et al, Nature Phys. (2016)

The Oscillators Ability to Mutually Interact Opens the Path to RF Communication between Neurons



Vowels Classification with Spin-Torque Oscillator Neural Network

Inputs: vowels

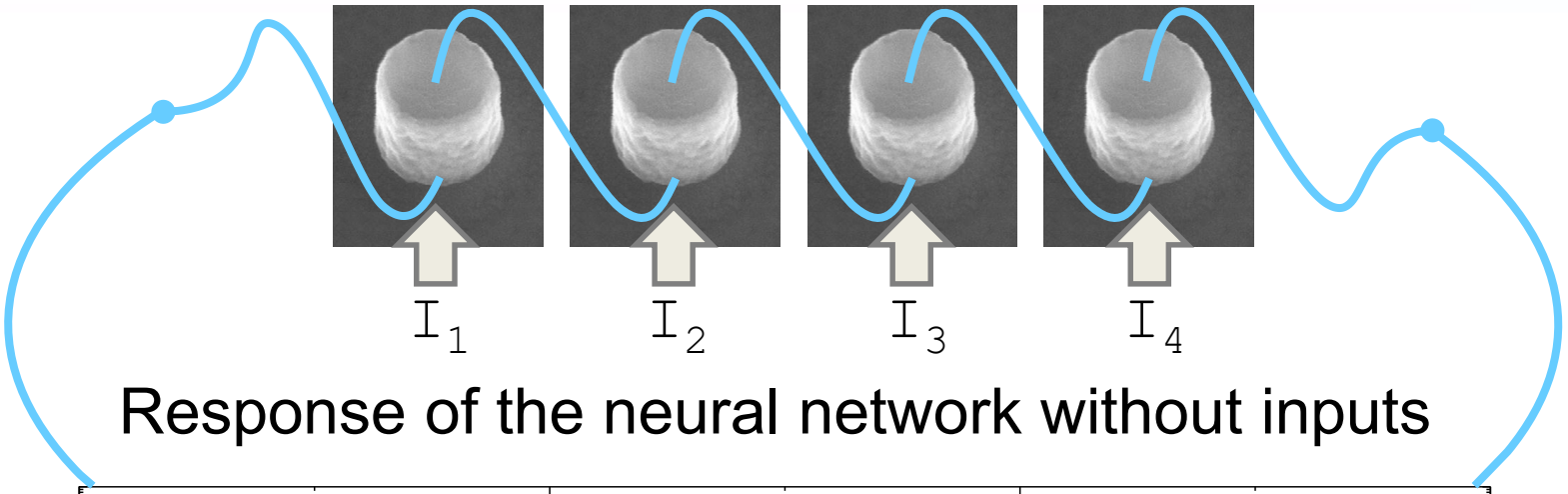


Hillebrands Michingan dataset

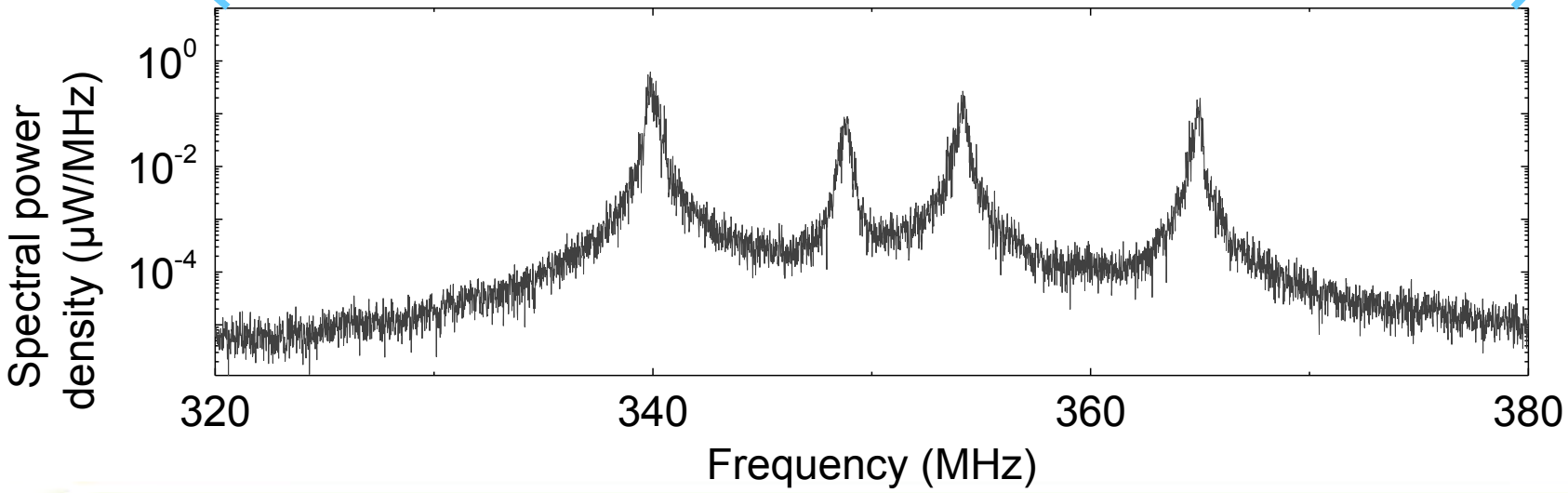
Magnetic Nano-Oscillators

Outputs: synchronized states

An Experimental Implementation

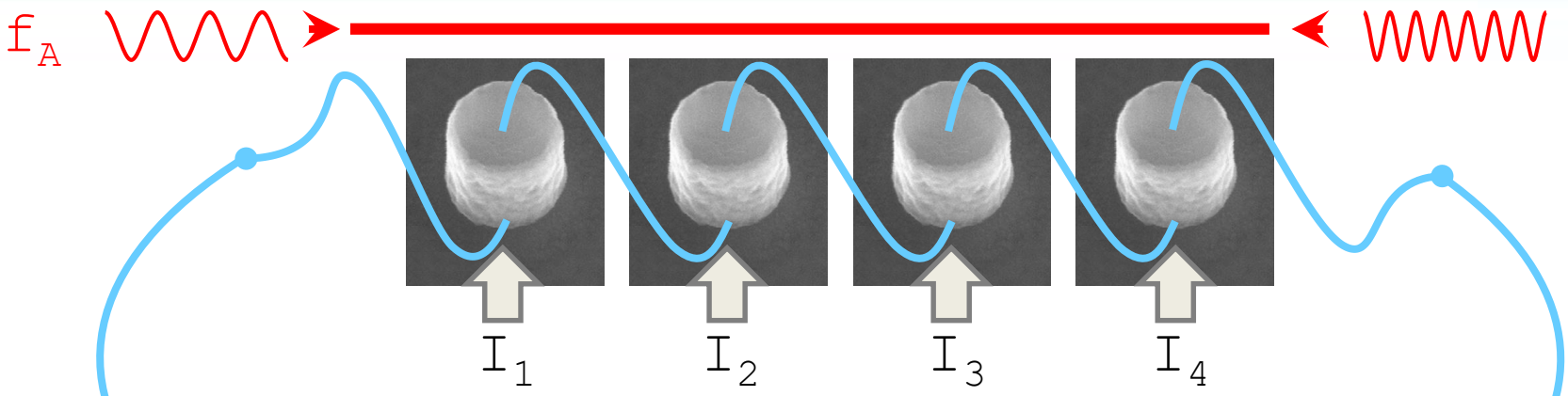


Response of the neural network without inputs

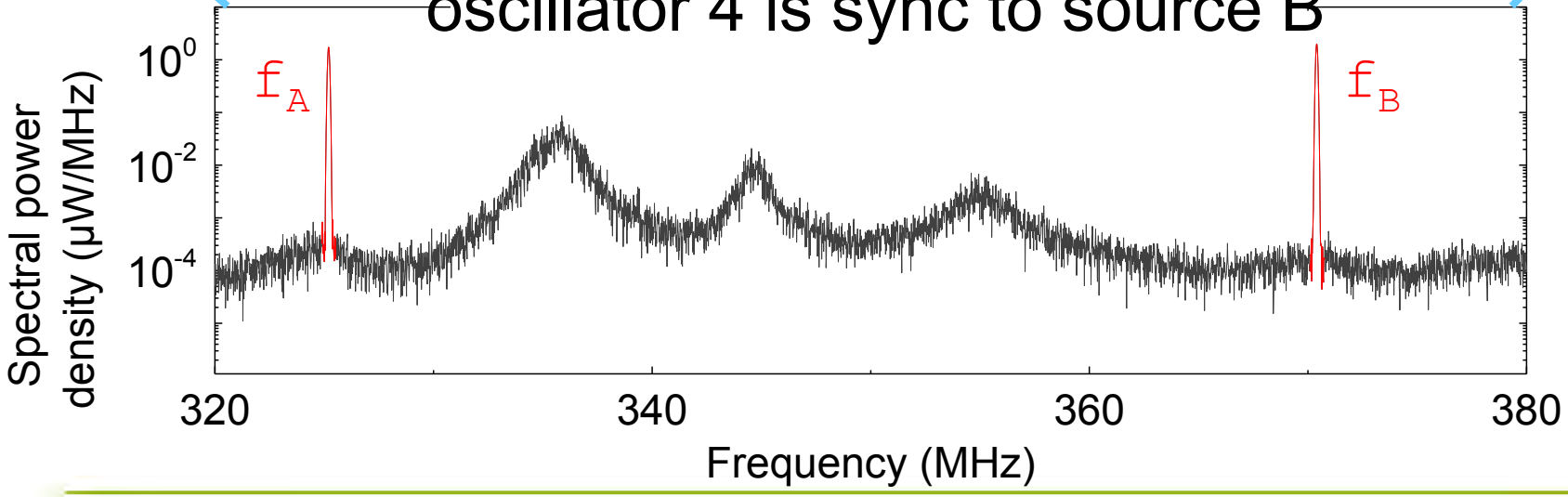


M. Romera, P. Talatchian et al, arXiv:1711.02704

Impact of an RF Input

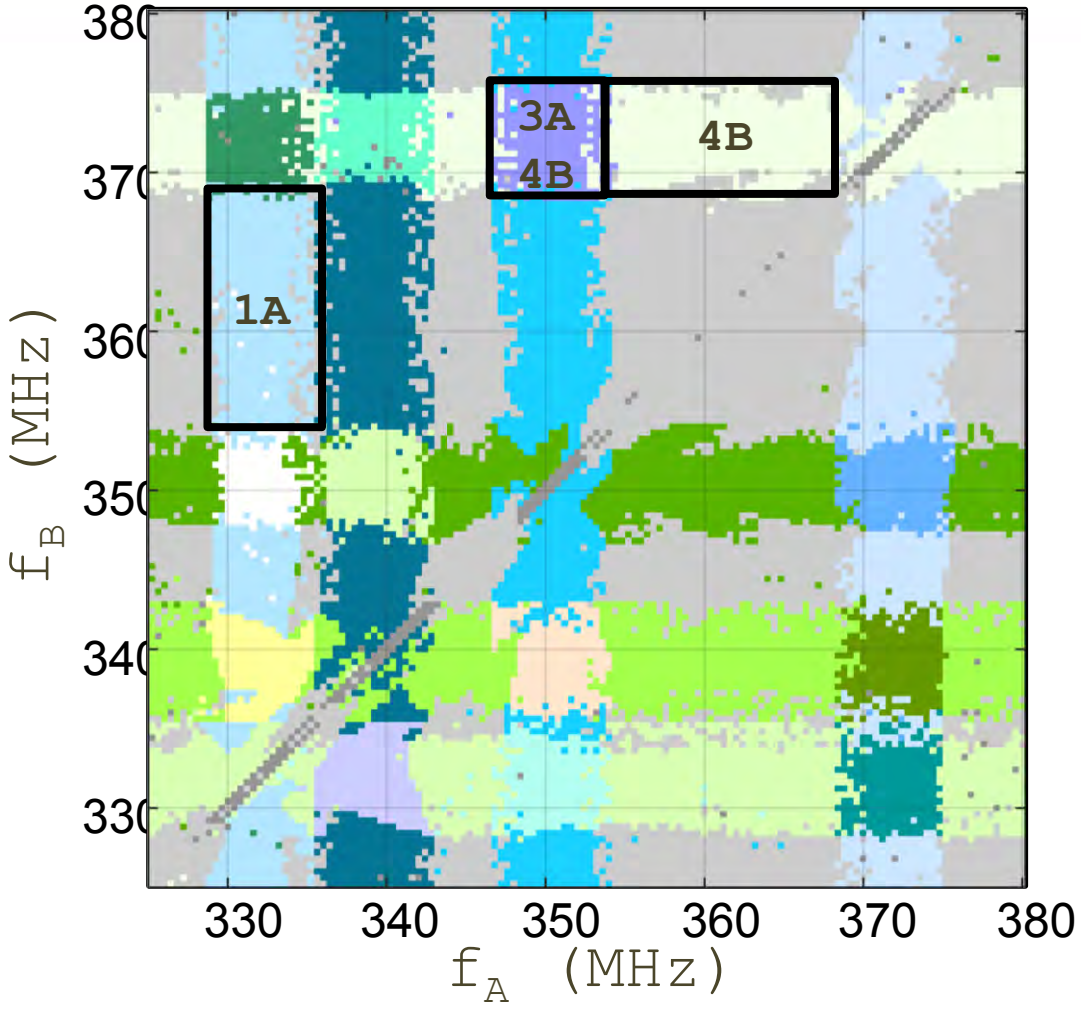


The inputs modify the oscillator responses:
oscillator 4 is sync to source B



M. Romera, P. Talatchian et al, arXiv:1711.02704

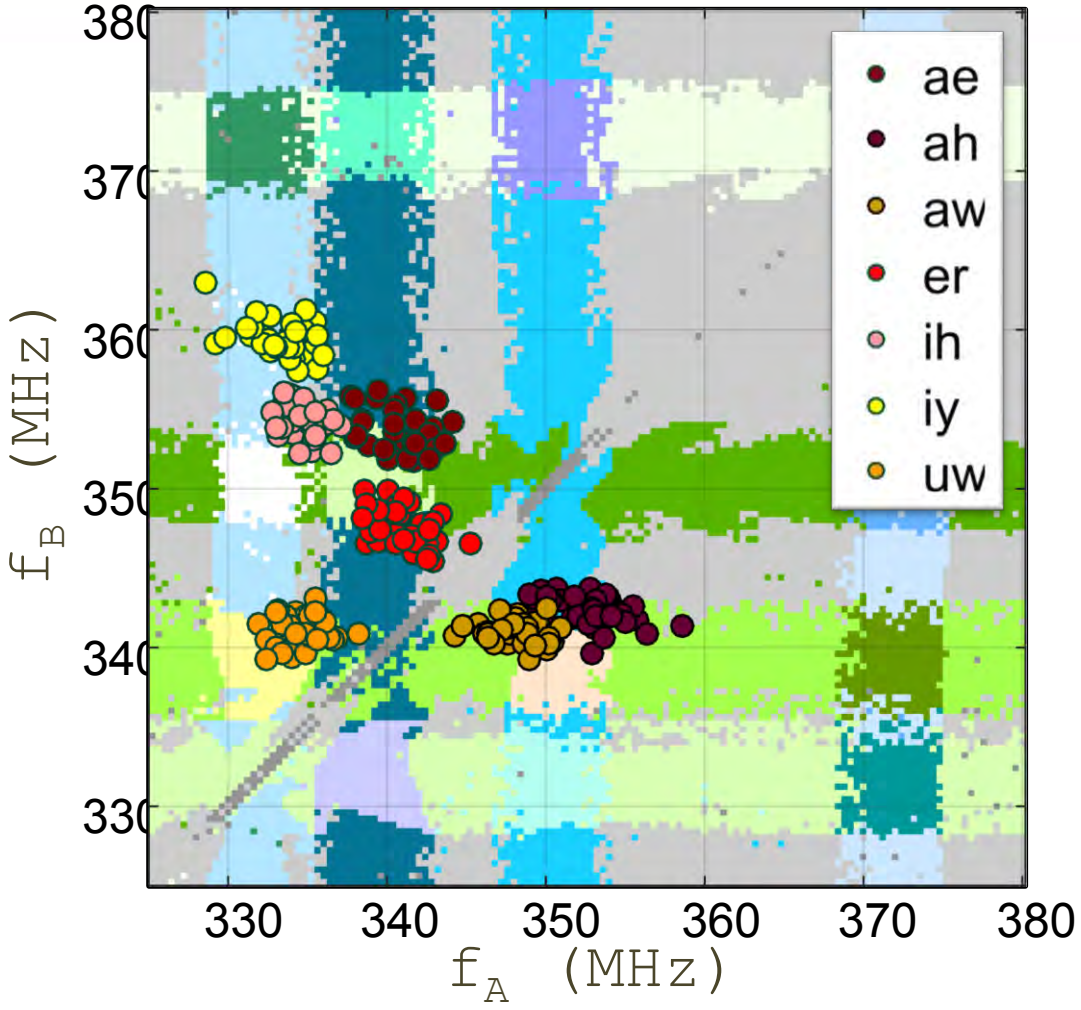
Whole Response Map



We summarize all these measurements in a map where the different synchronization states have different colors

M. Romera, P. Talatchian et al, arXiv:1711.02704

Whole Response Map



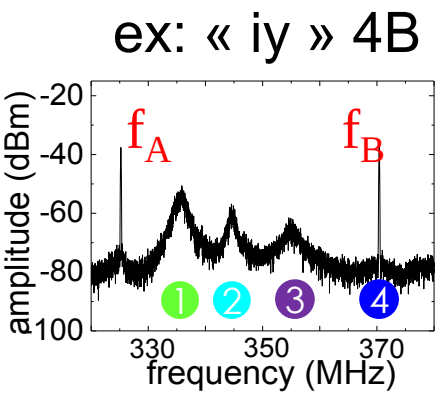
For classification, all the points corresponding to one vowel should fall in a single synchronization region

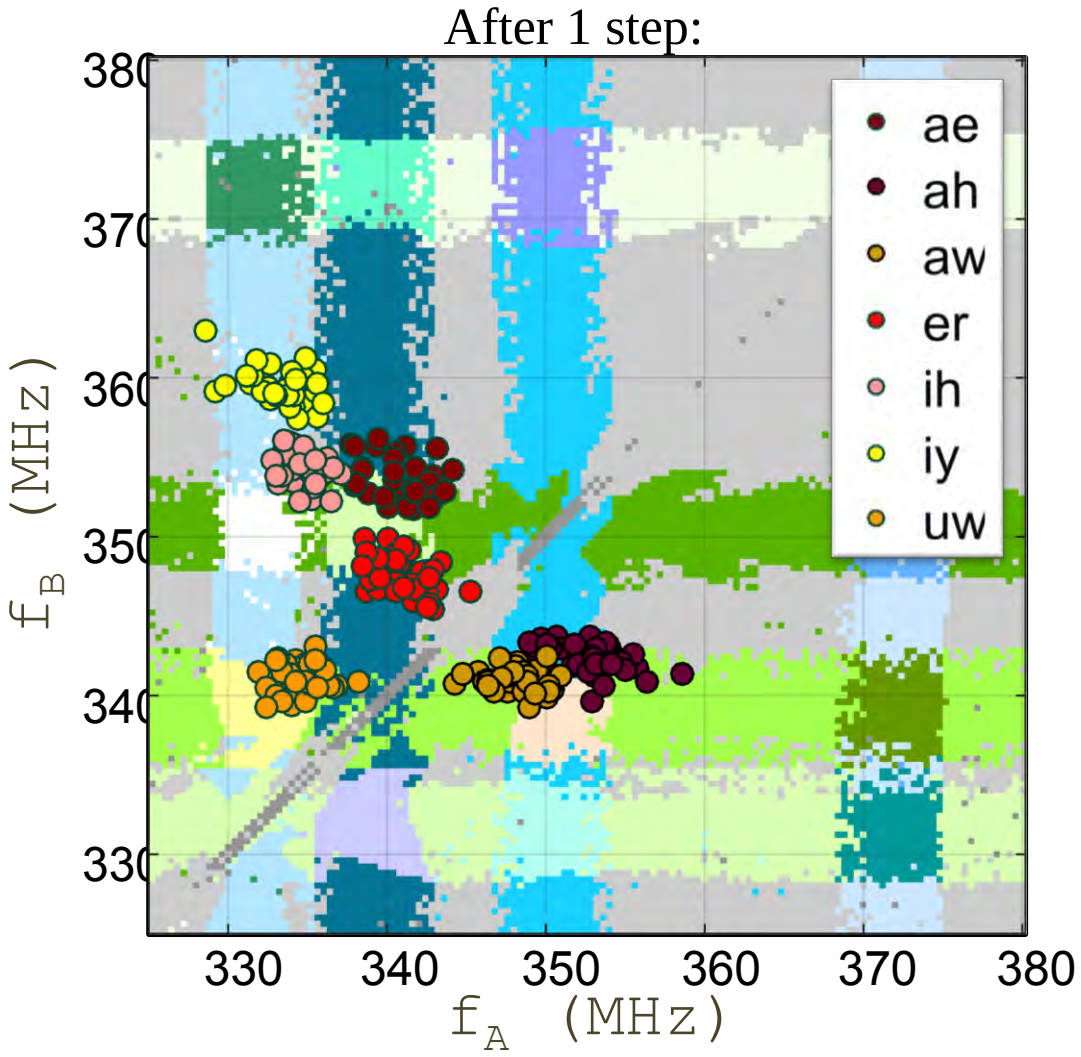
M. Romera, P. Talatchian et al, arXiv:1711.02704

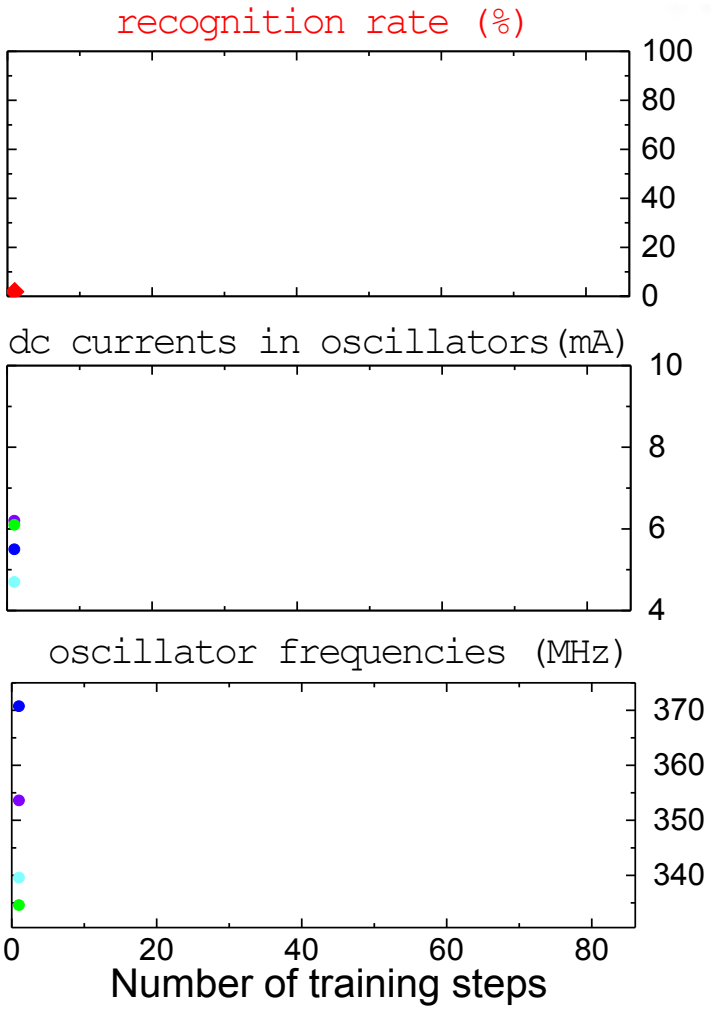
We Train the Network by Tuning the Currents through the Oscillators

Following an online learning rule

Experimental set-up ⟵ ⟶ Computer (Learning algorithm)

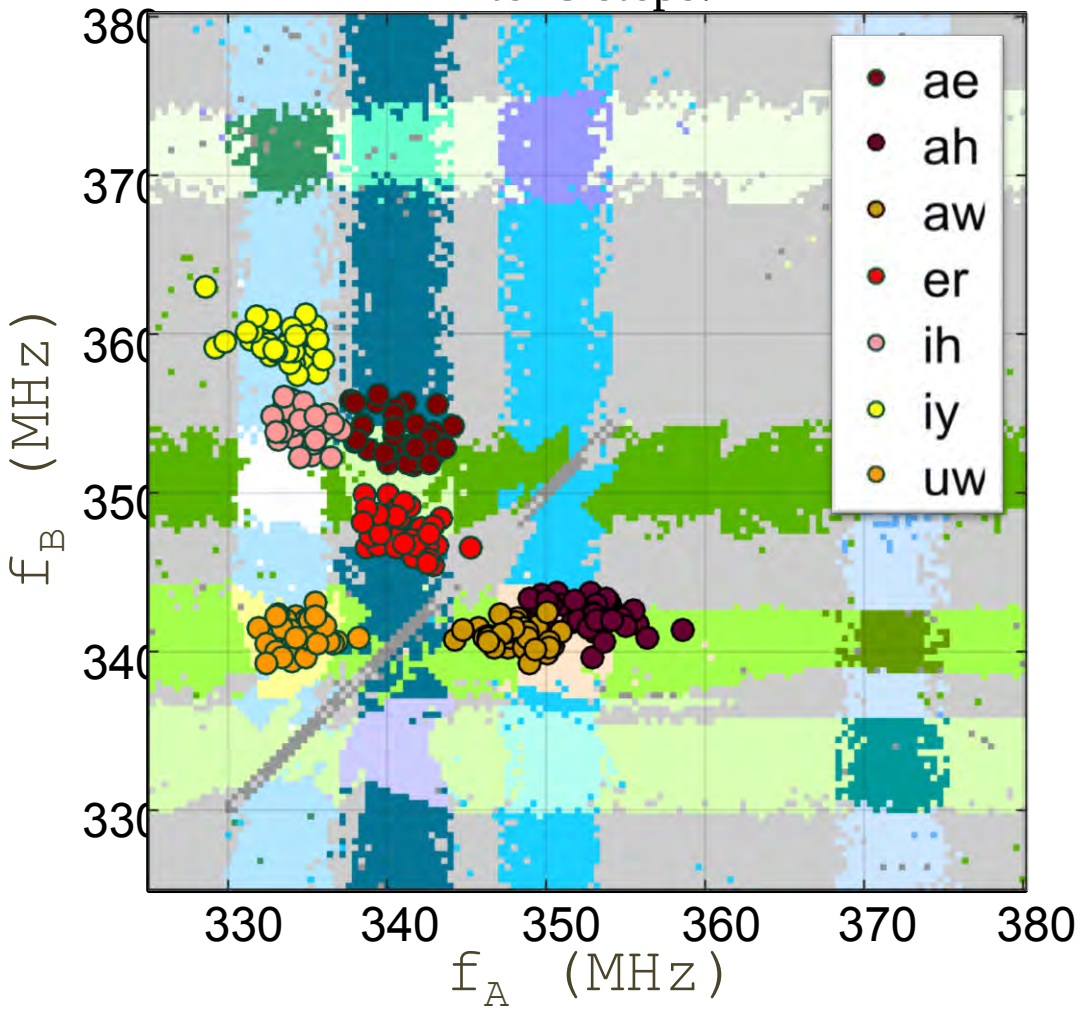


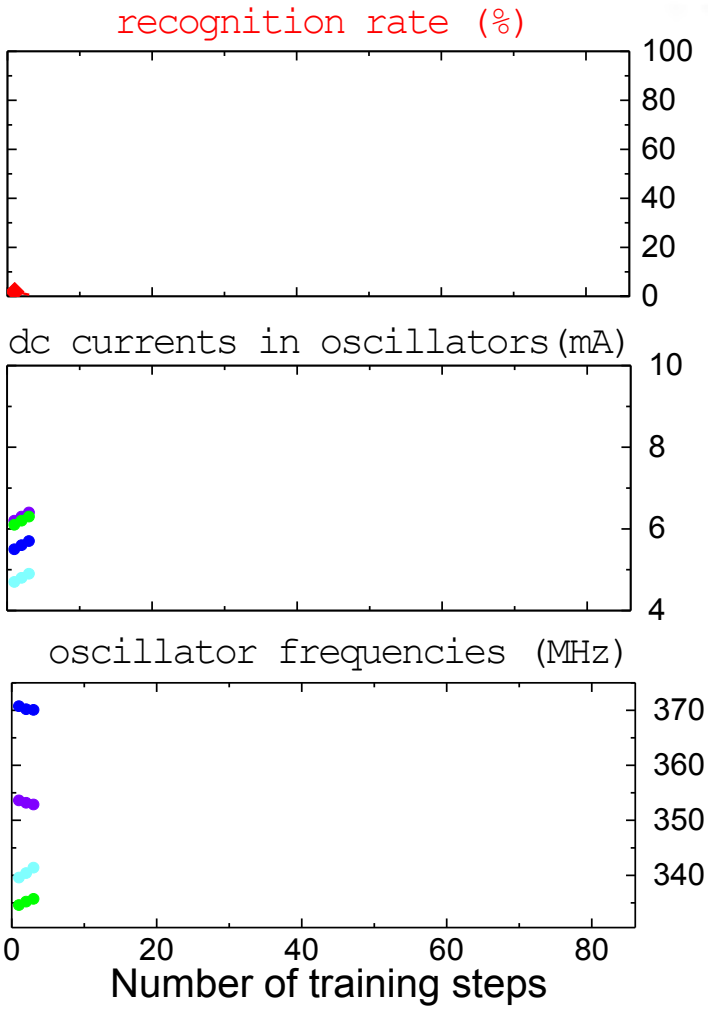




M. Romera, P. Talatchian et al, arXiv:1711.02704

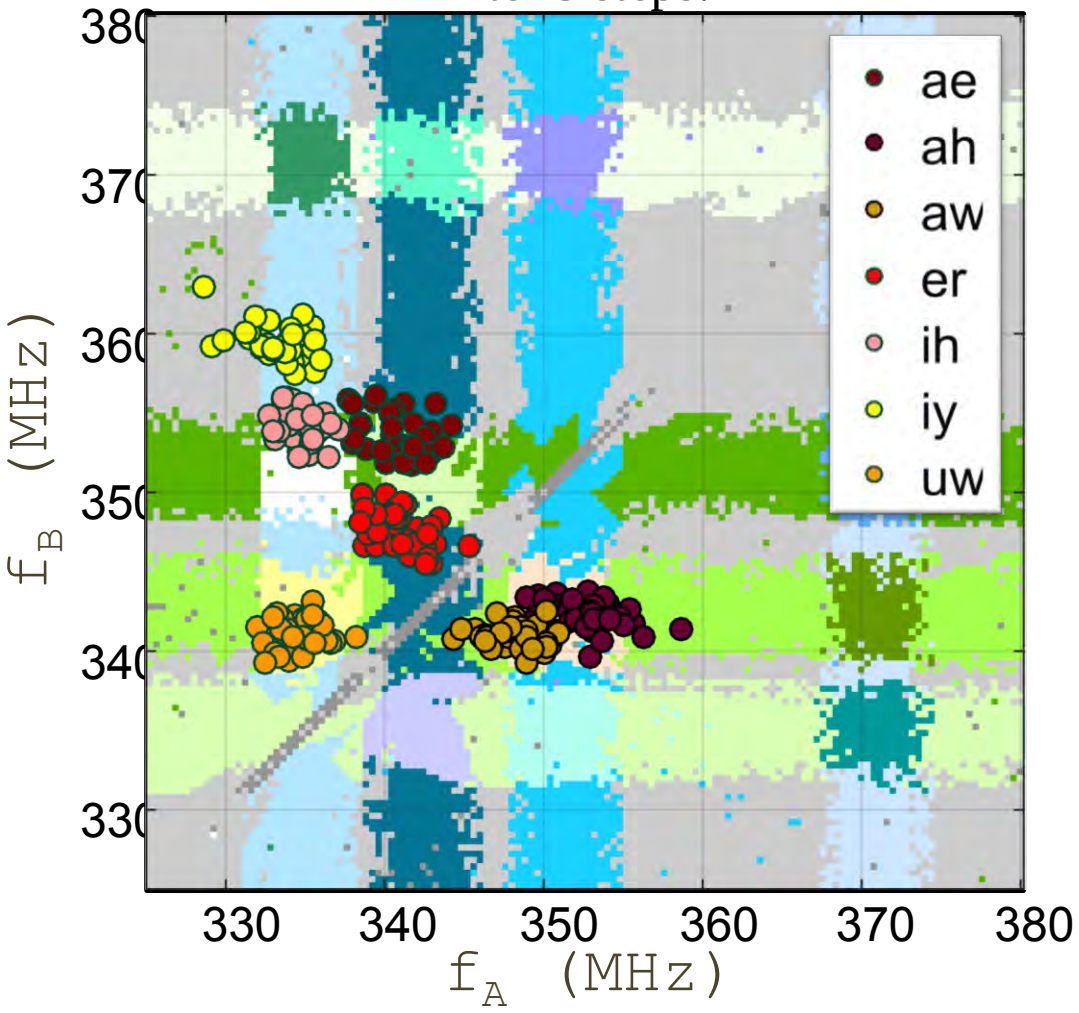
After 3 steps:

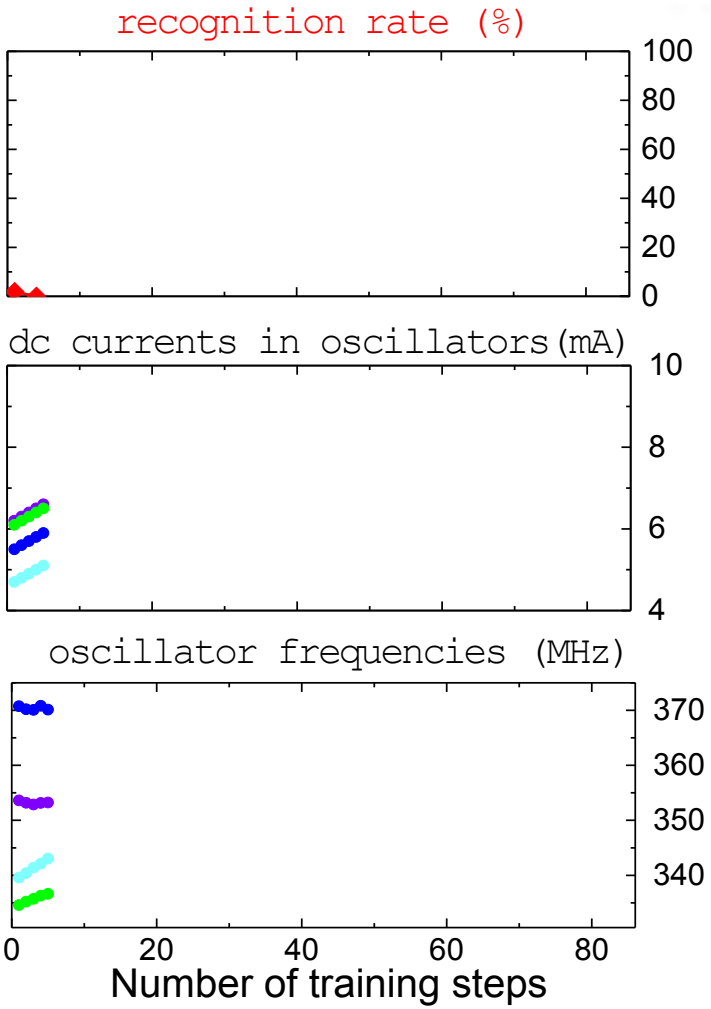




M. Romera, P. Talatchian et al, arXiv:1711.02704

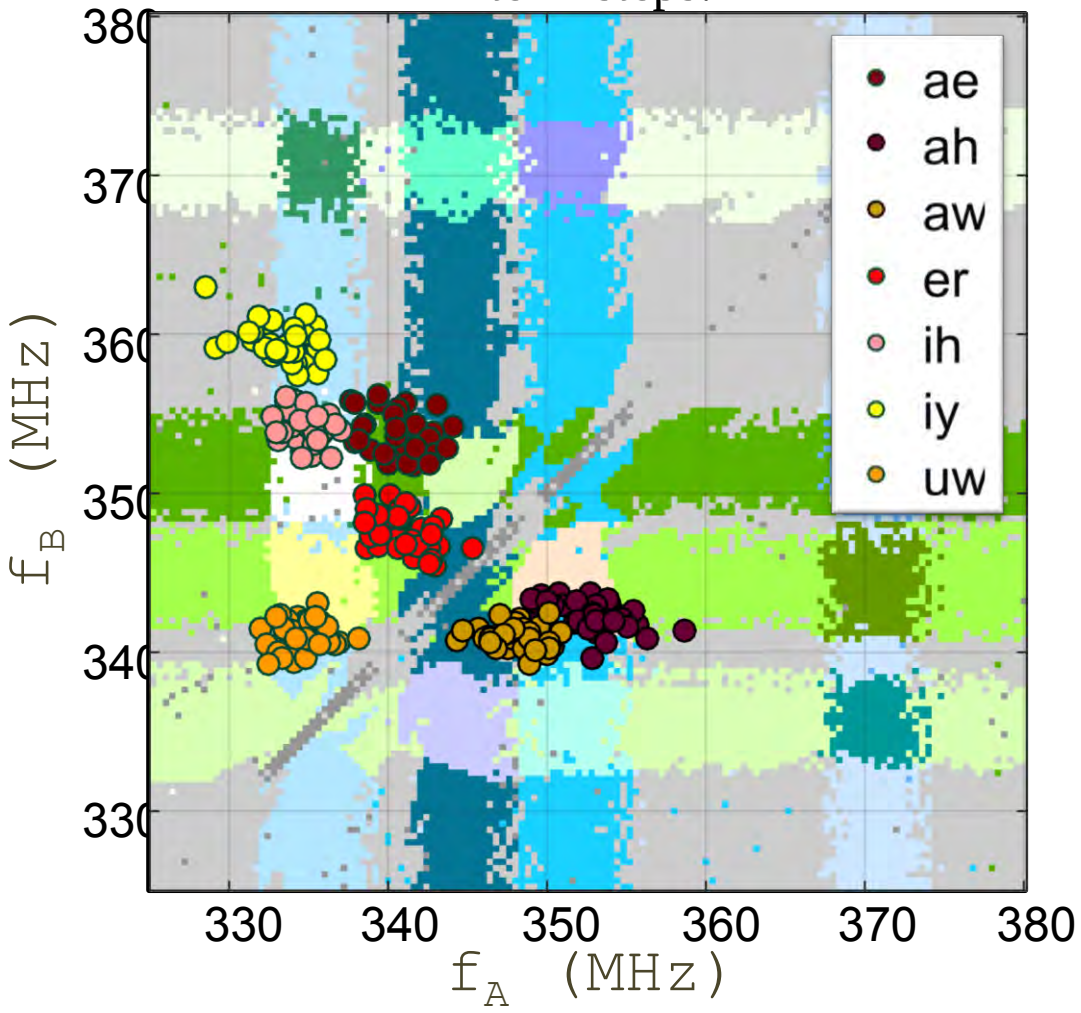
After 5 steps:

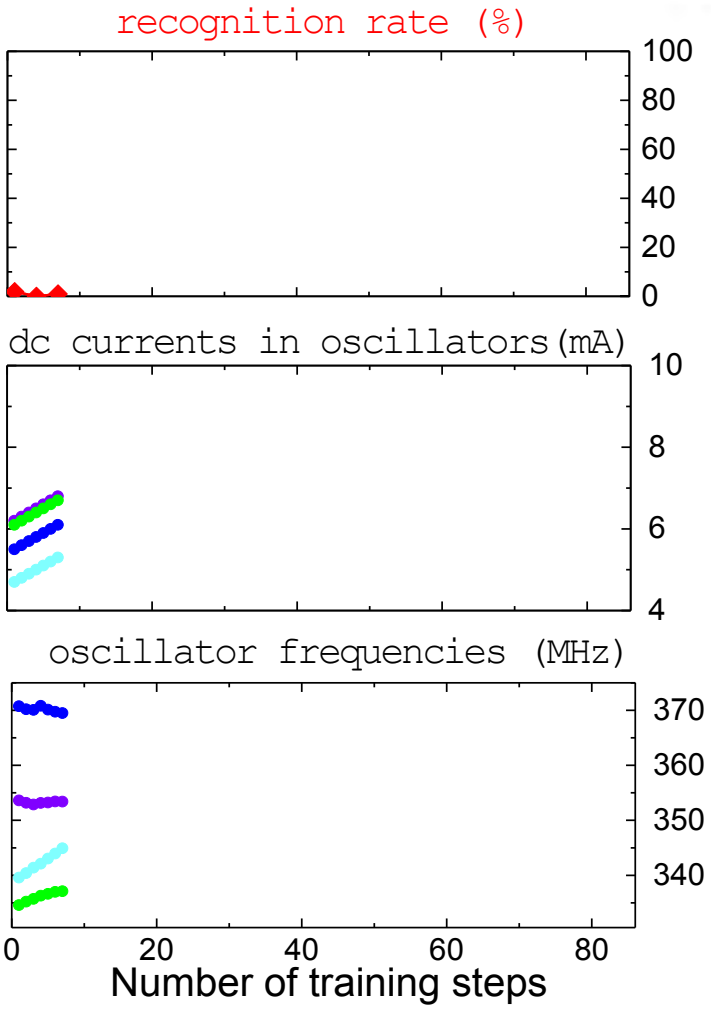




M. Romera, P. Talatchian et al, arXiv:1711.02704

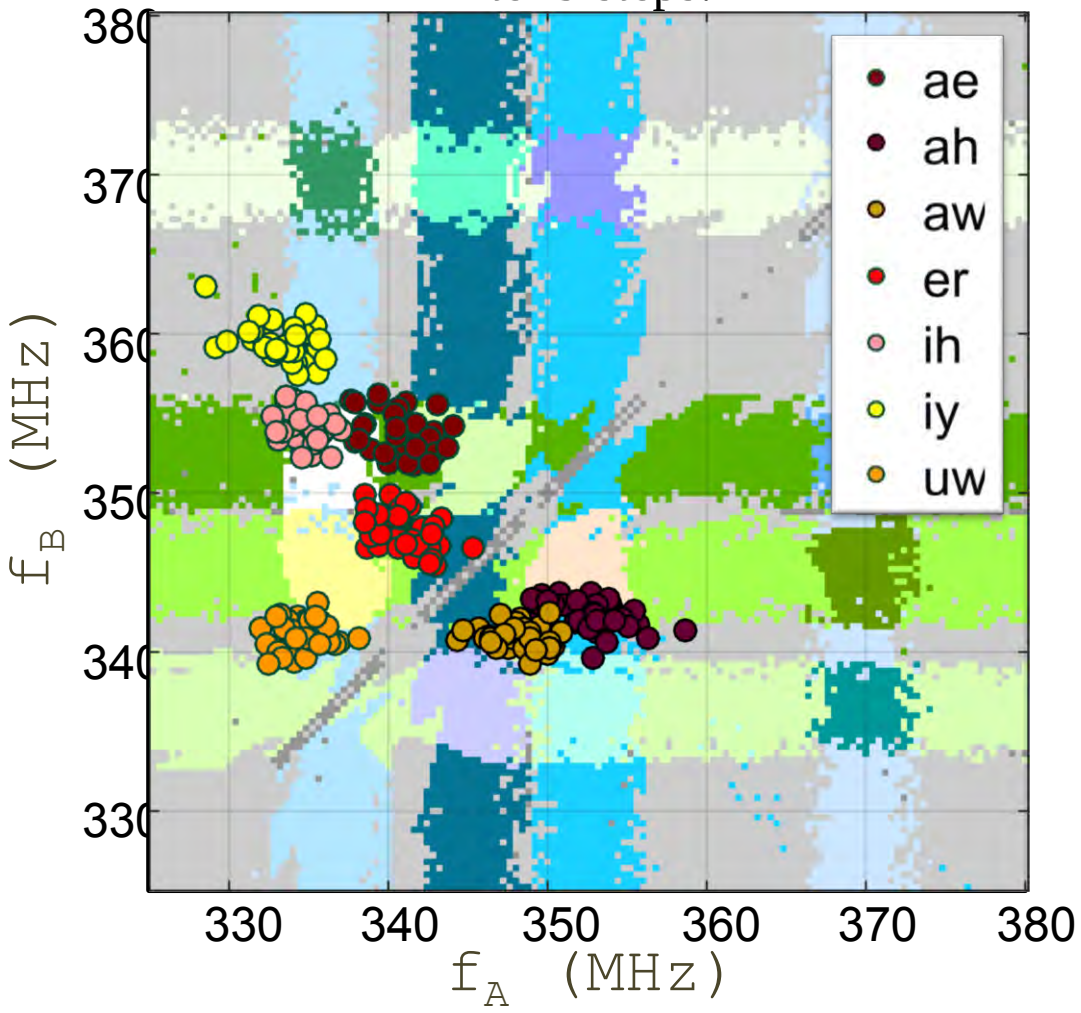
After 7 steps:

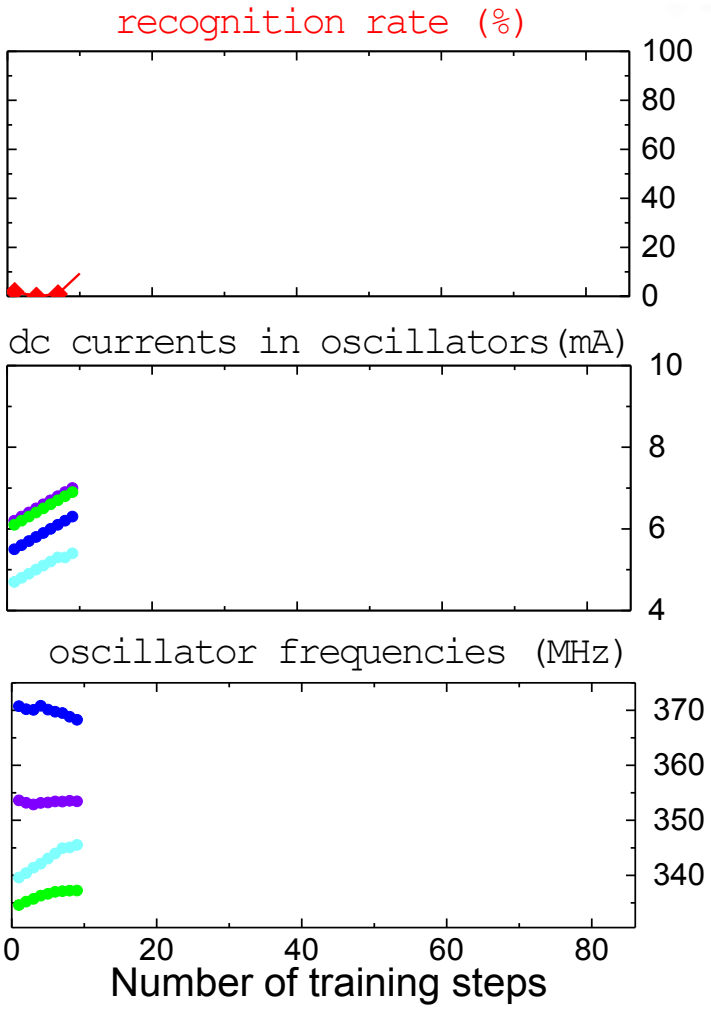




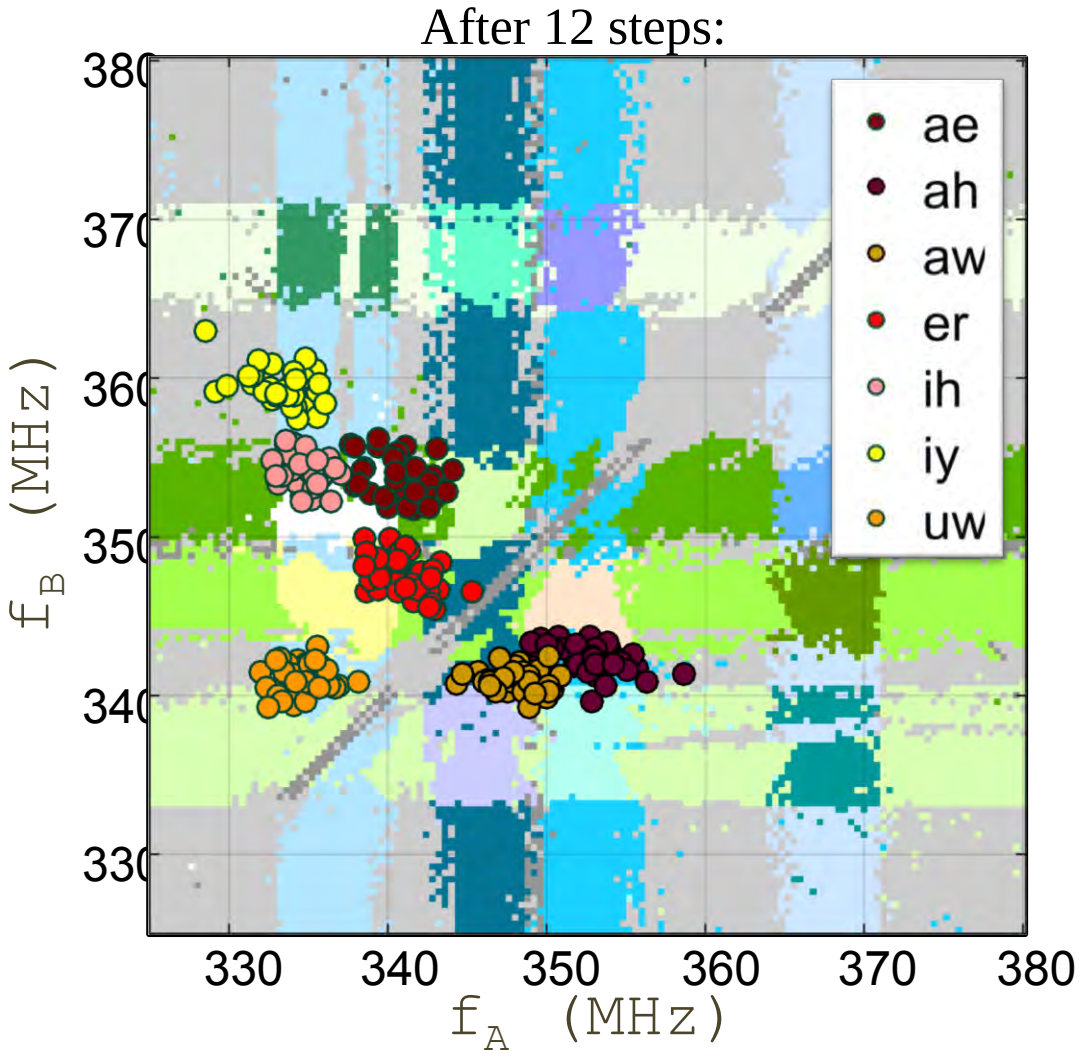
M. Romera, P. Talatchian et al, arXiv:1711.02704

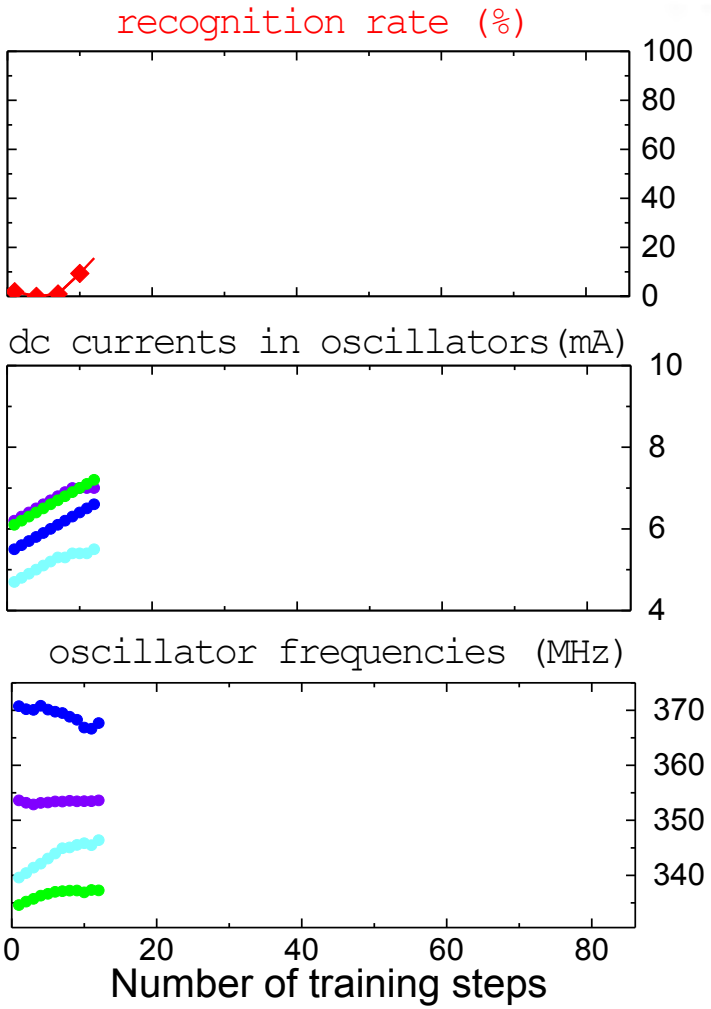
After 9 steps:





M. Romera, P. Talatchian et al, arXiv:1711.02704





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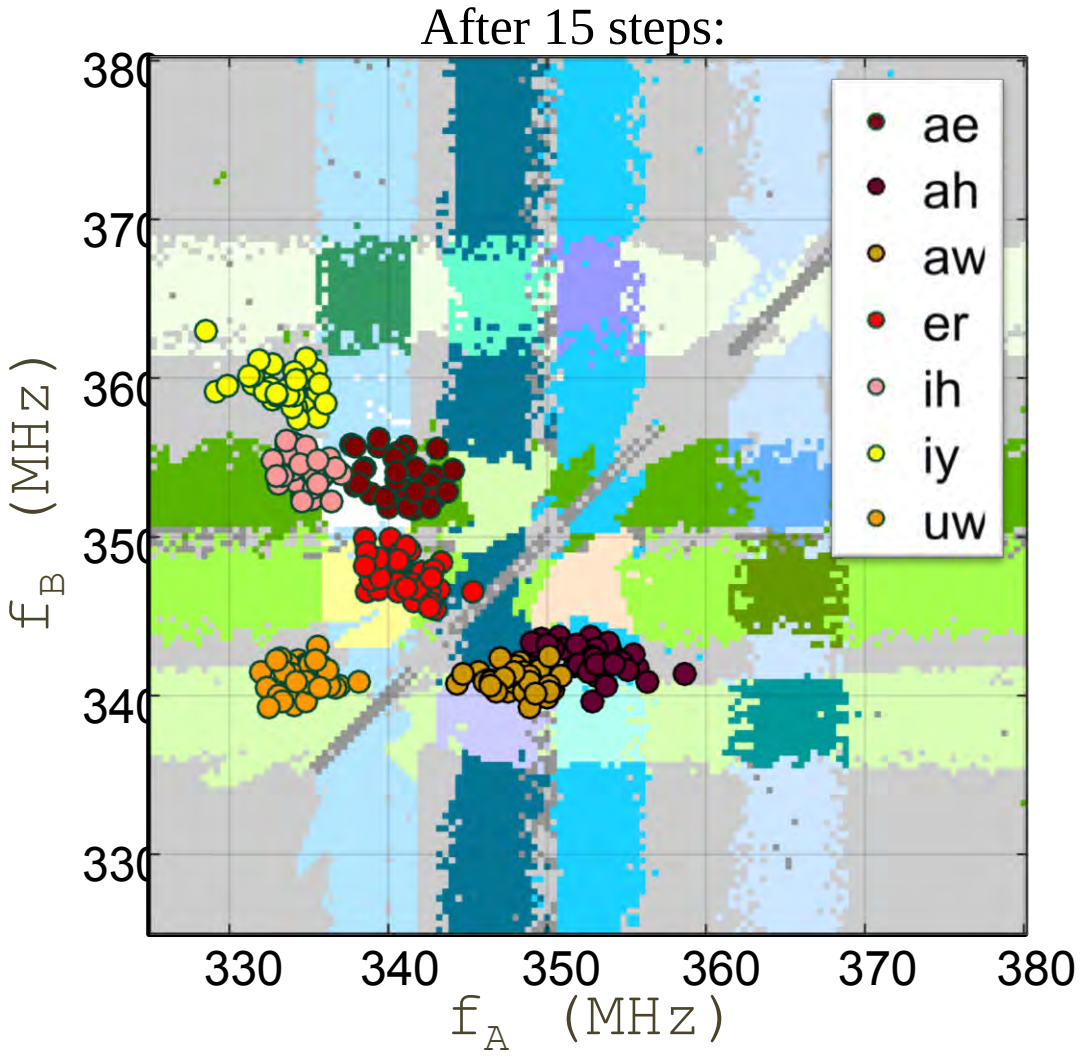

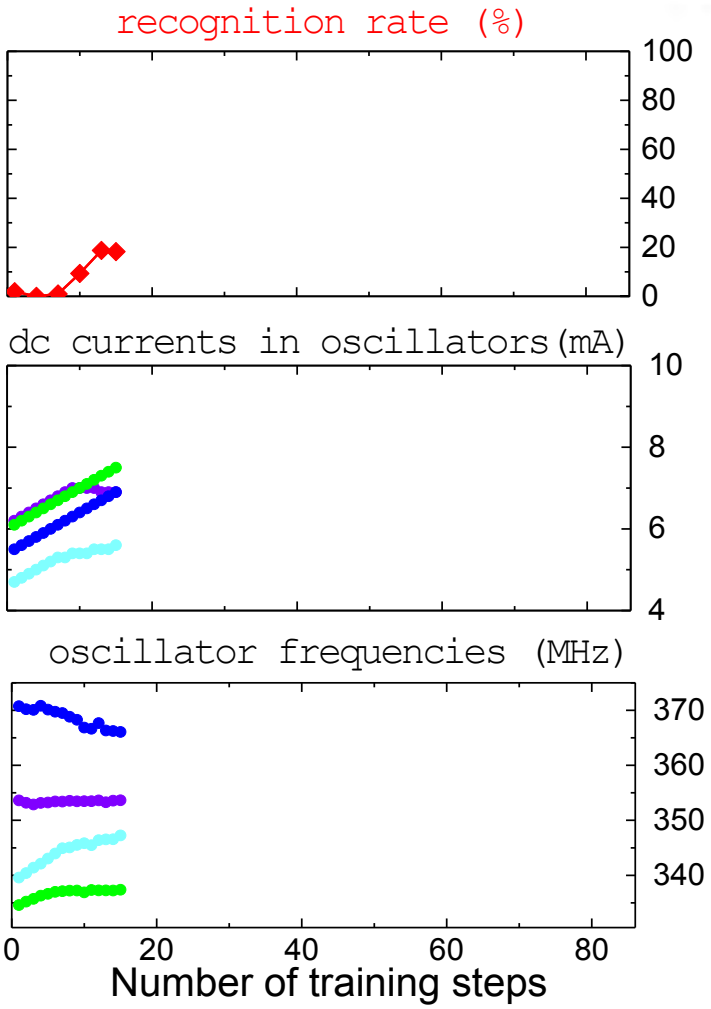

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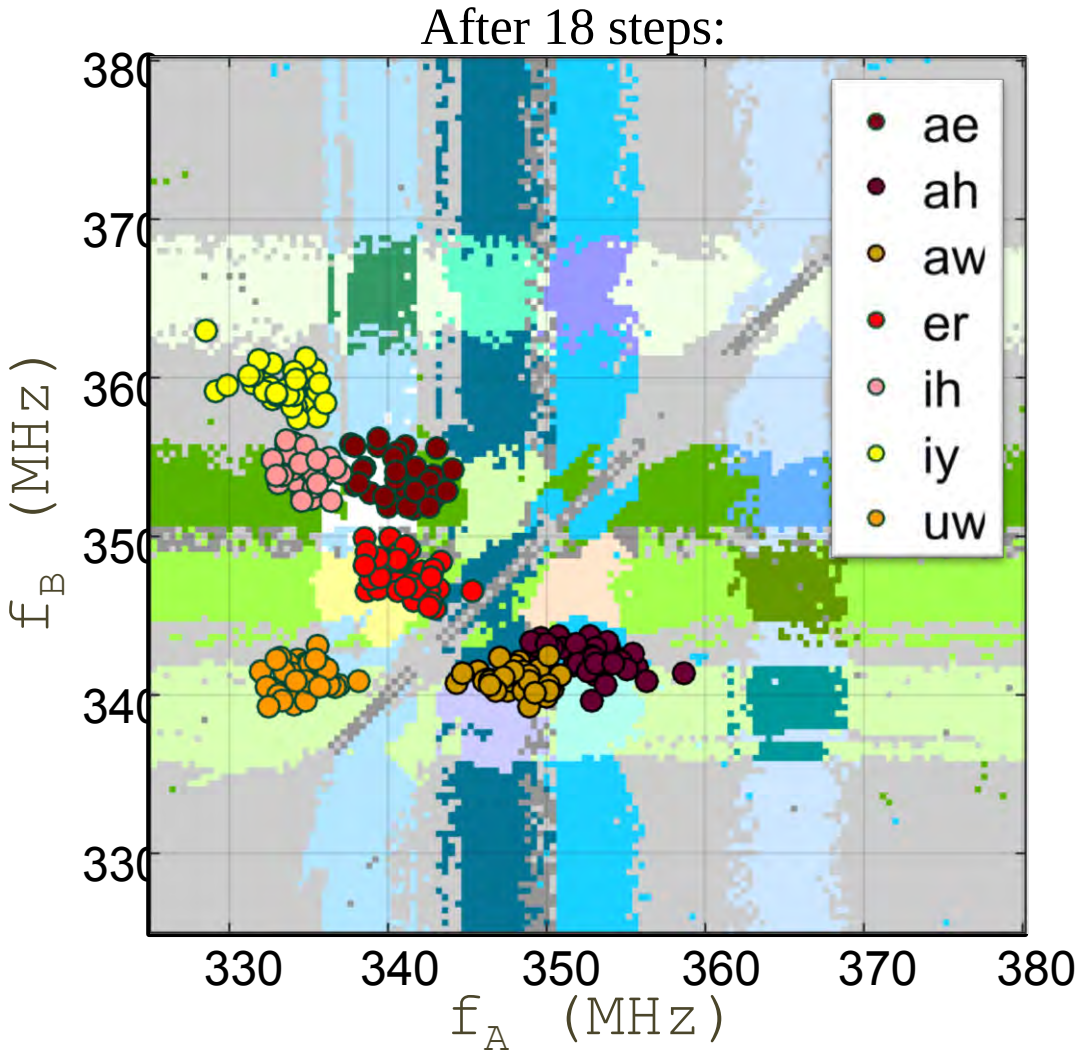
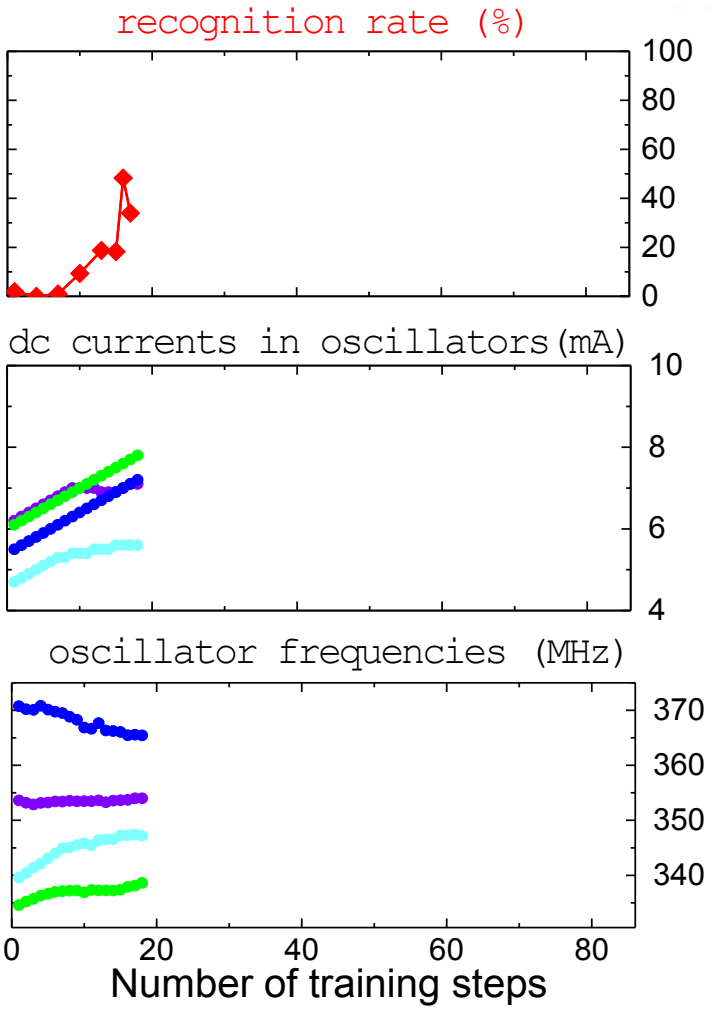
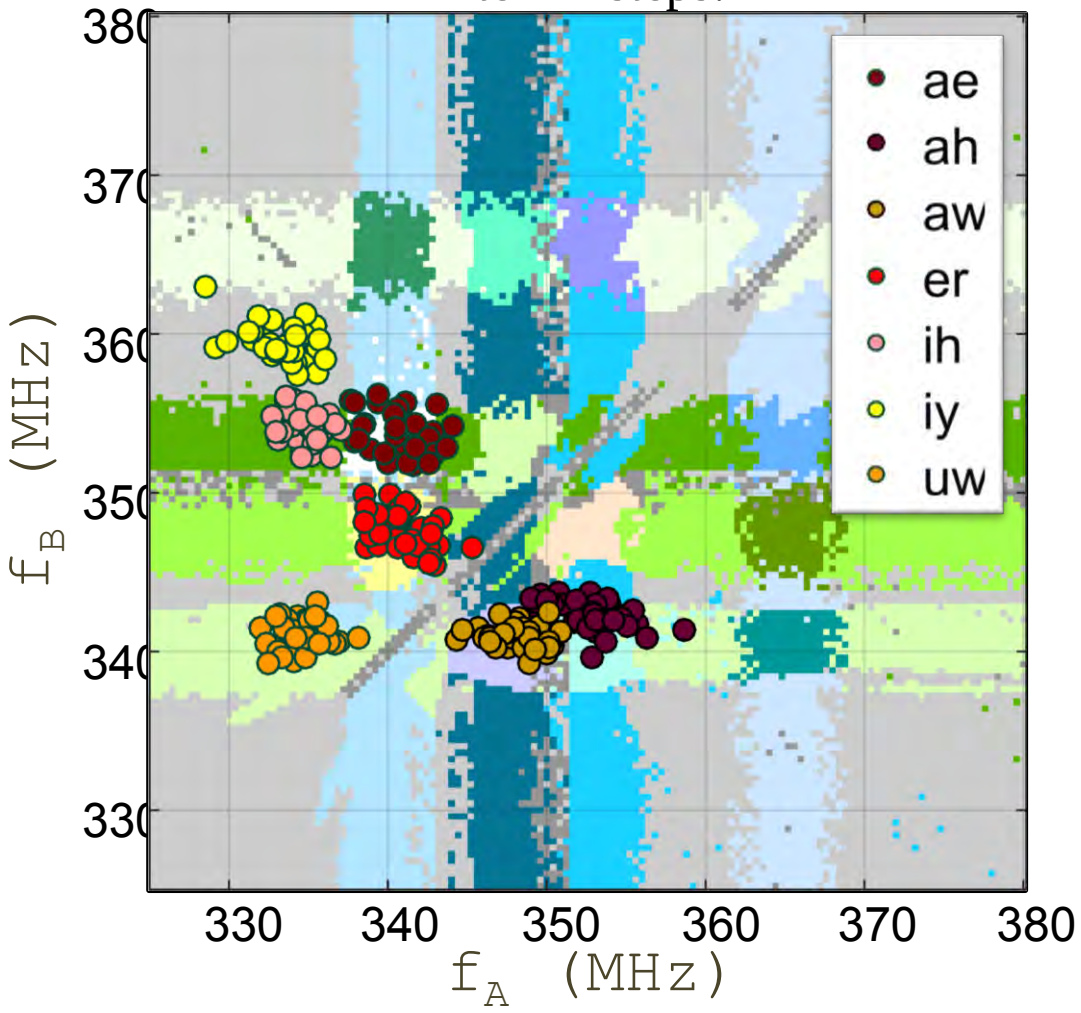
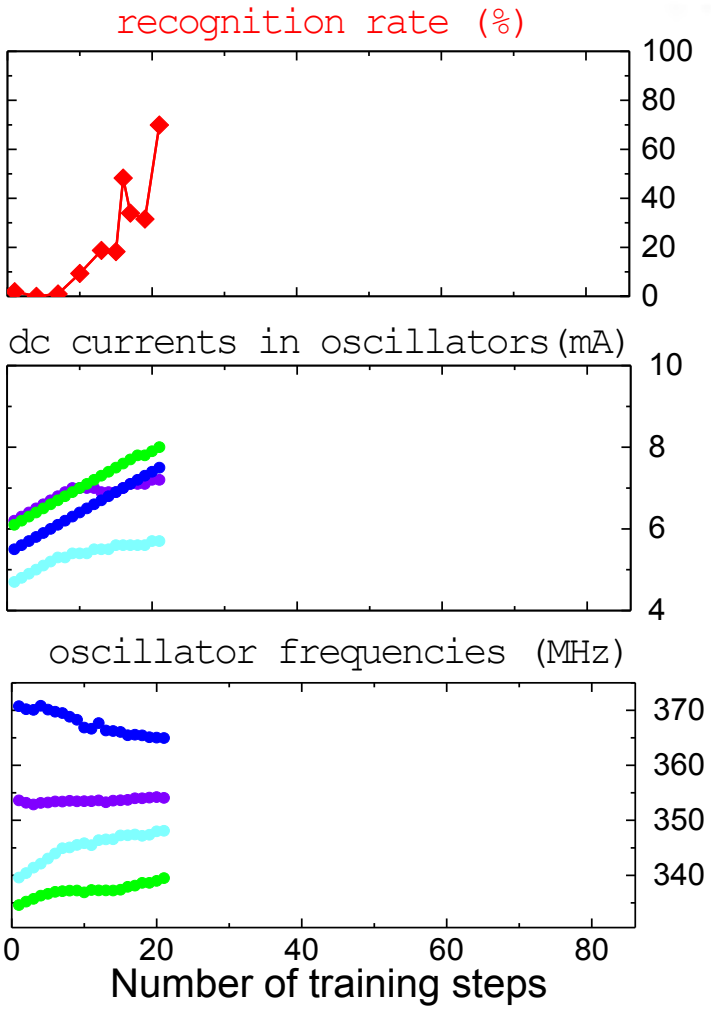




M. Romera, P. Talatchian et al, arXiv:1711.02704

After 21 steps:





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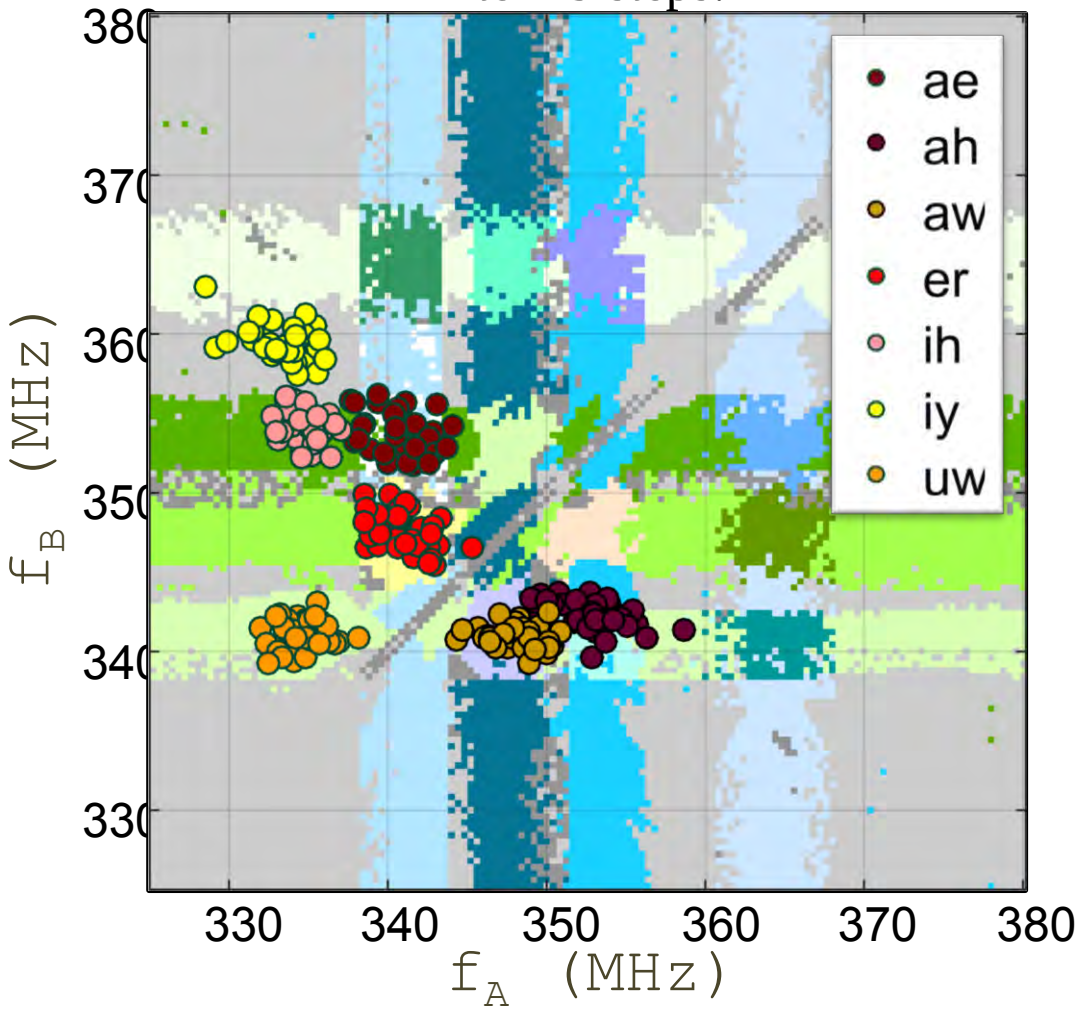
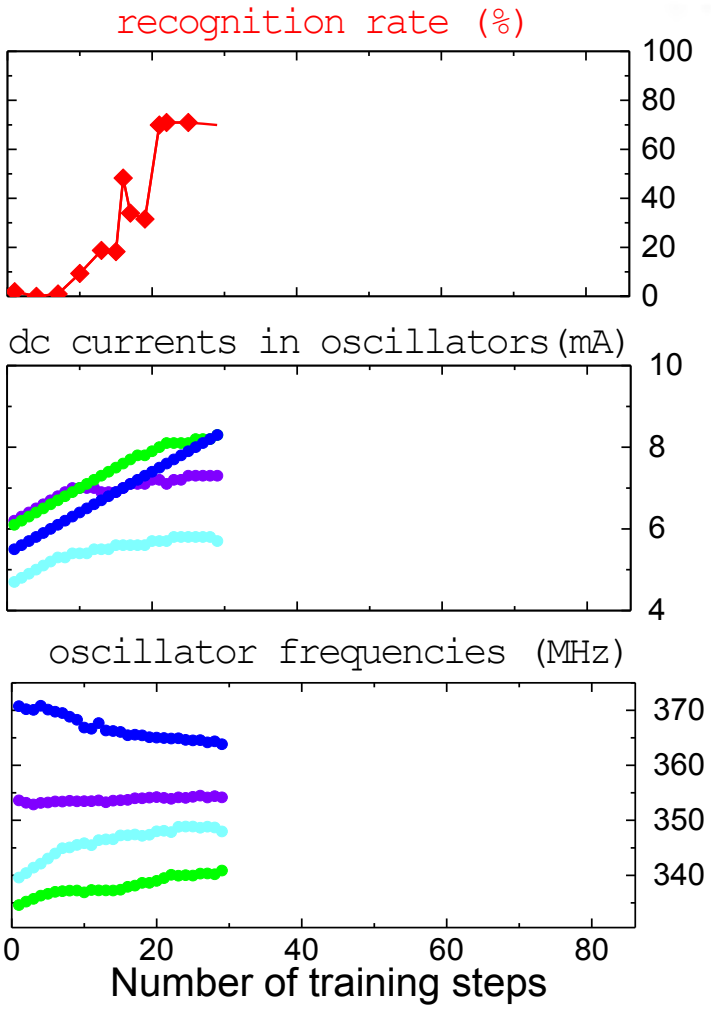
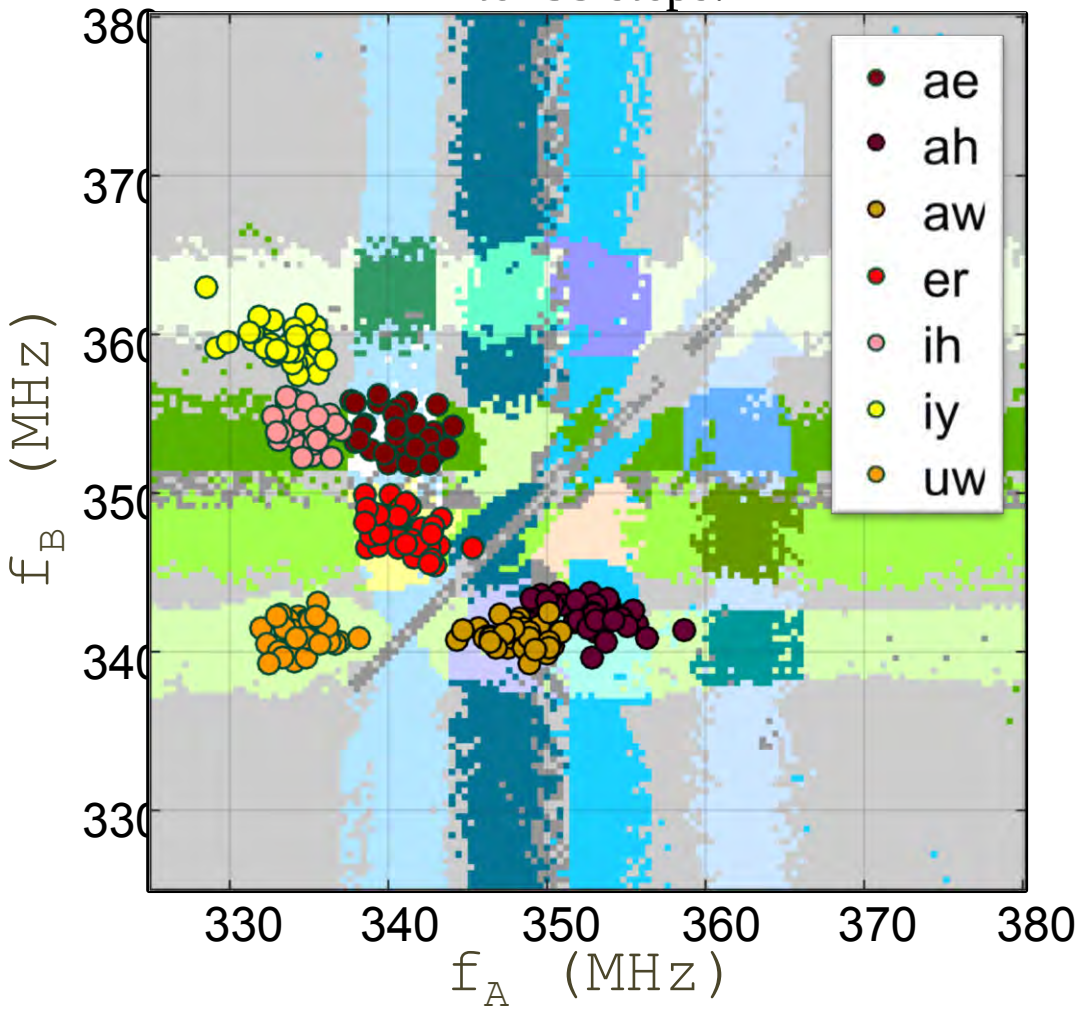
After 29 steps:

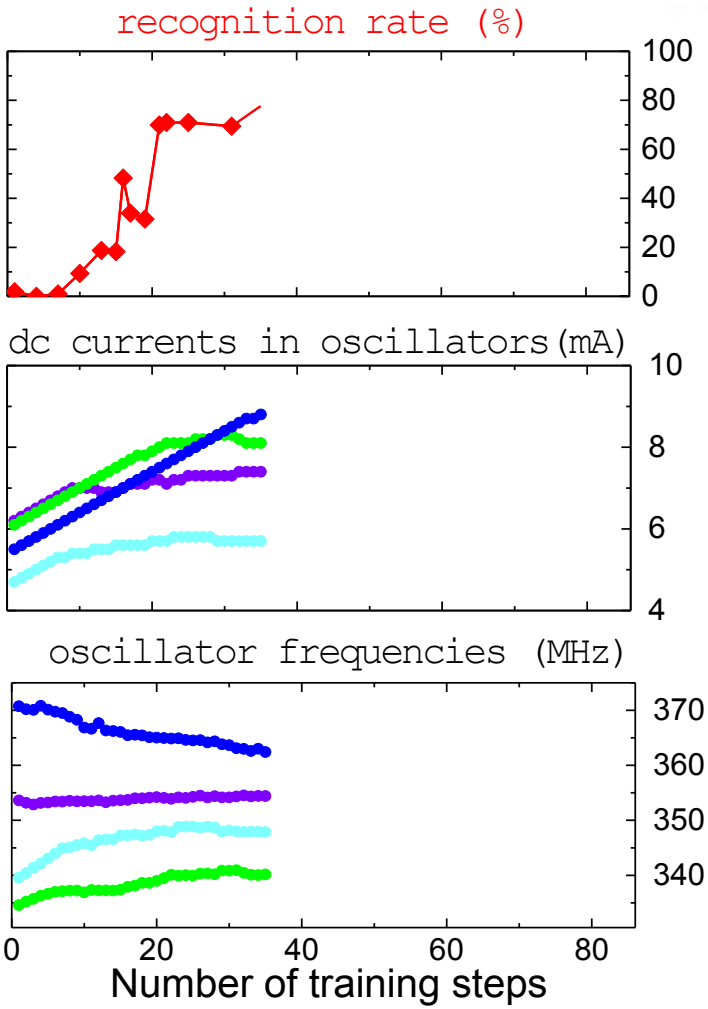




M. Romera, P. Talatchian et al, arXiv:1711.02704

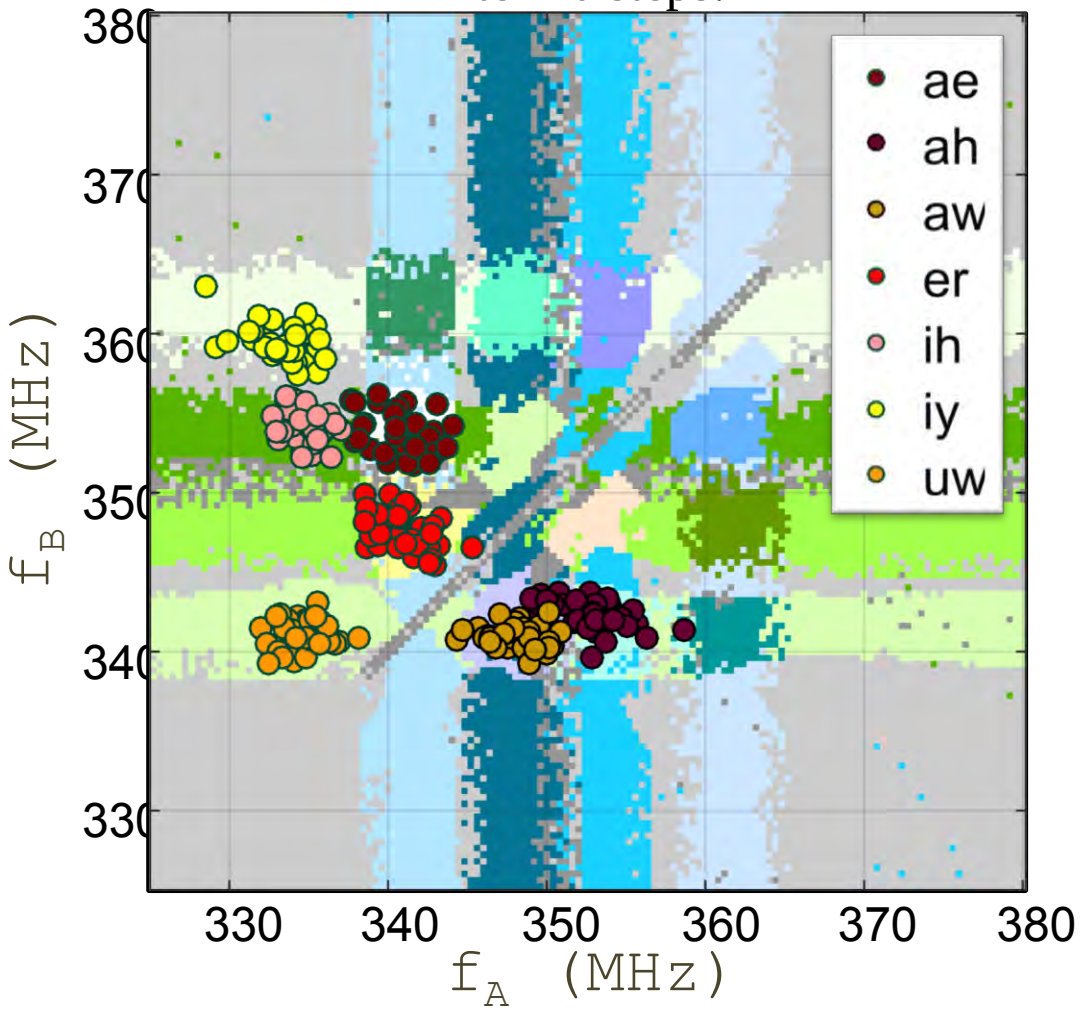
After 35 steps:

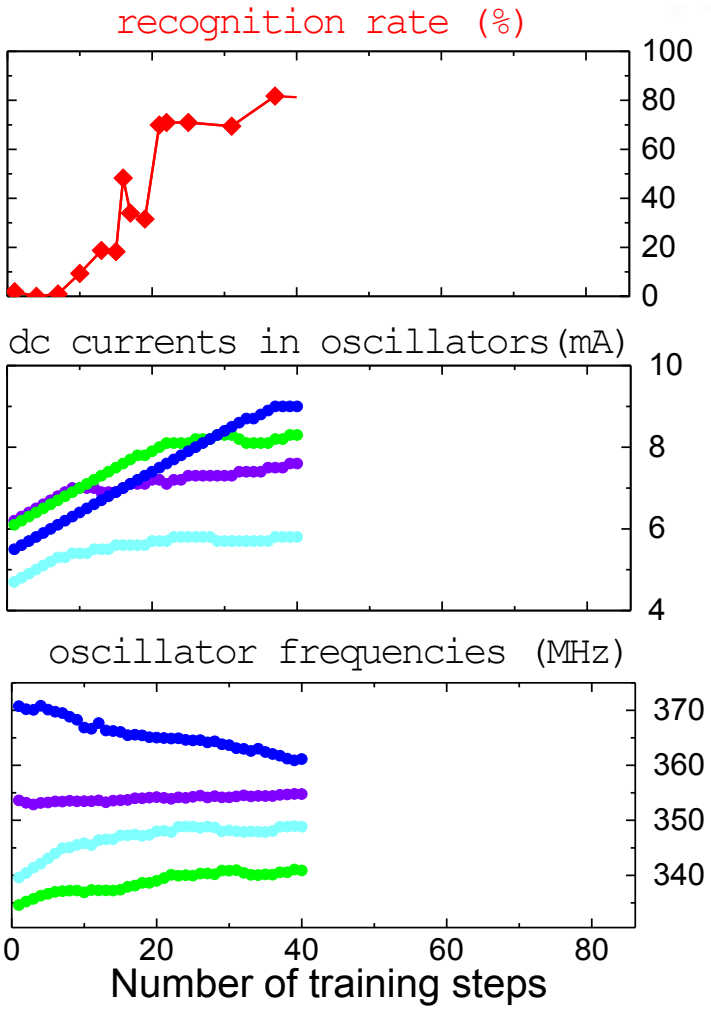




M. Romera, P. Talatchian et al, arXiv:1711.02704

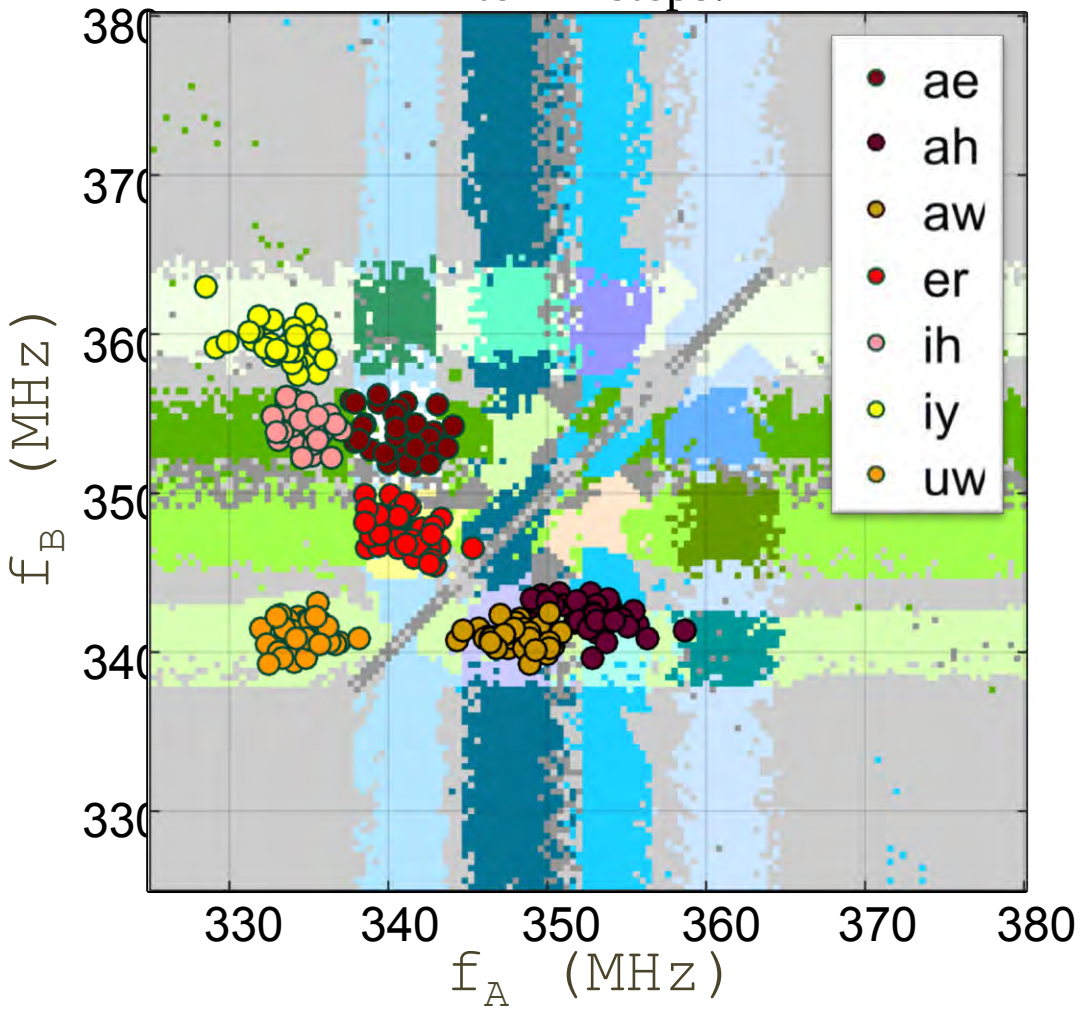
After 40 steps:

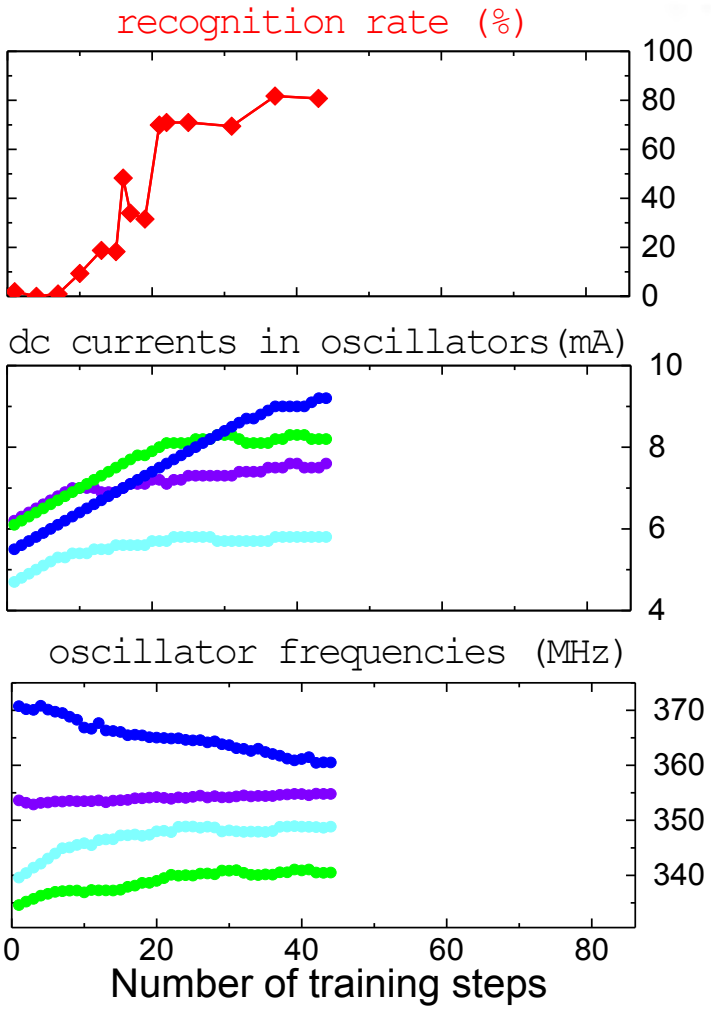




M. Romera, P. Talatchian et al, arXiv:1711.02704

After 44 steps:





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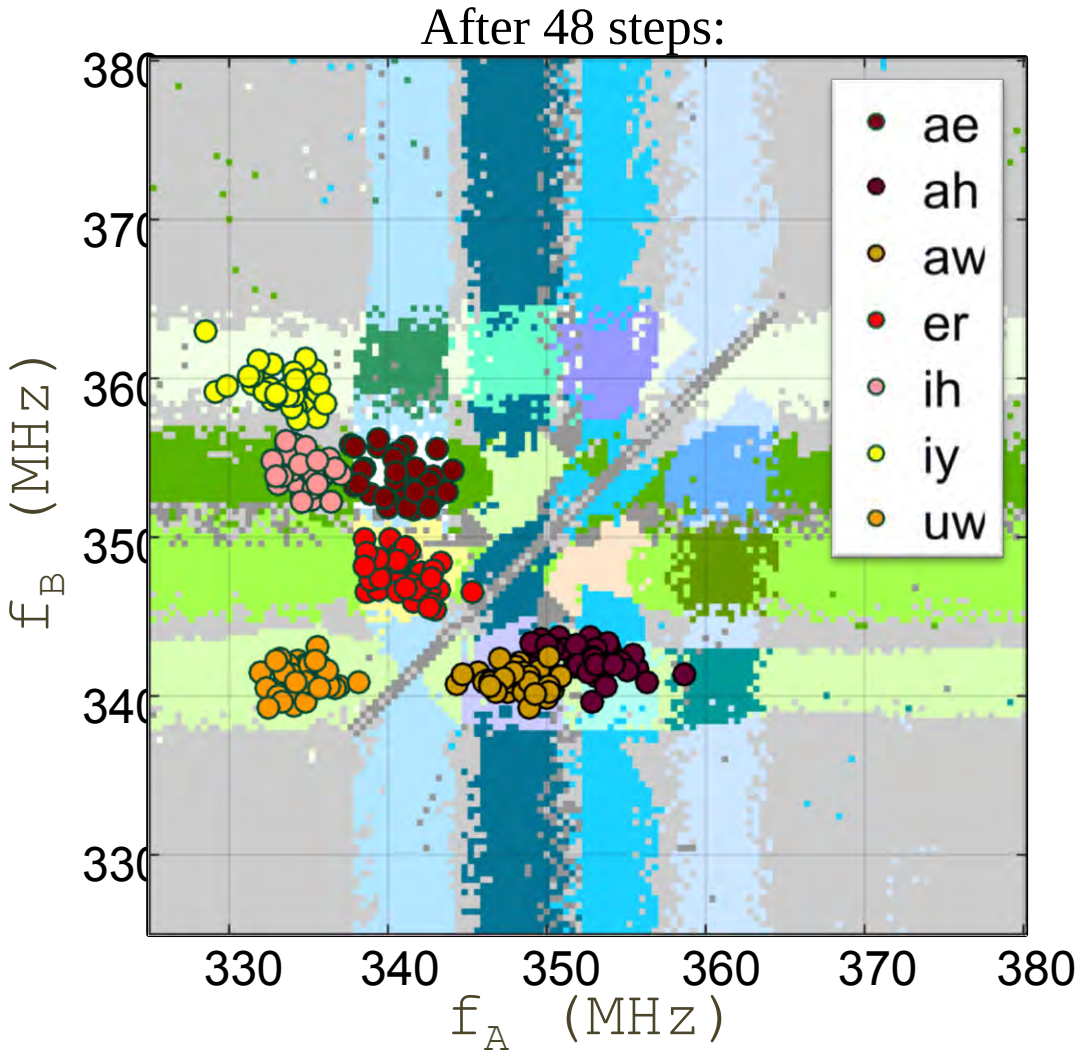

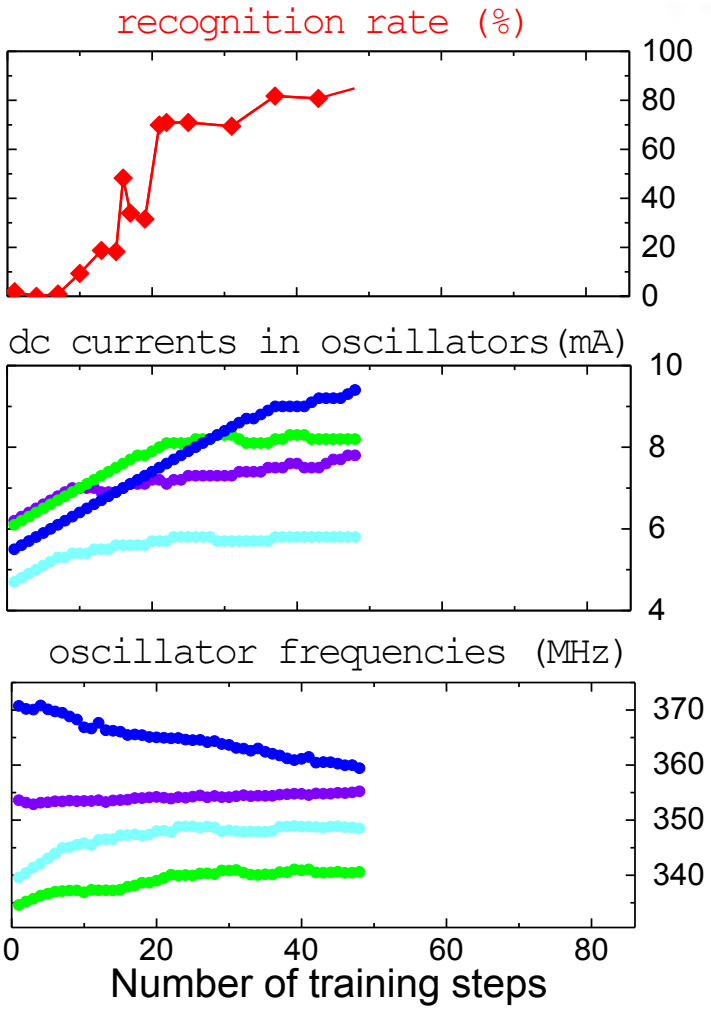

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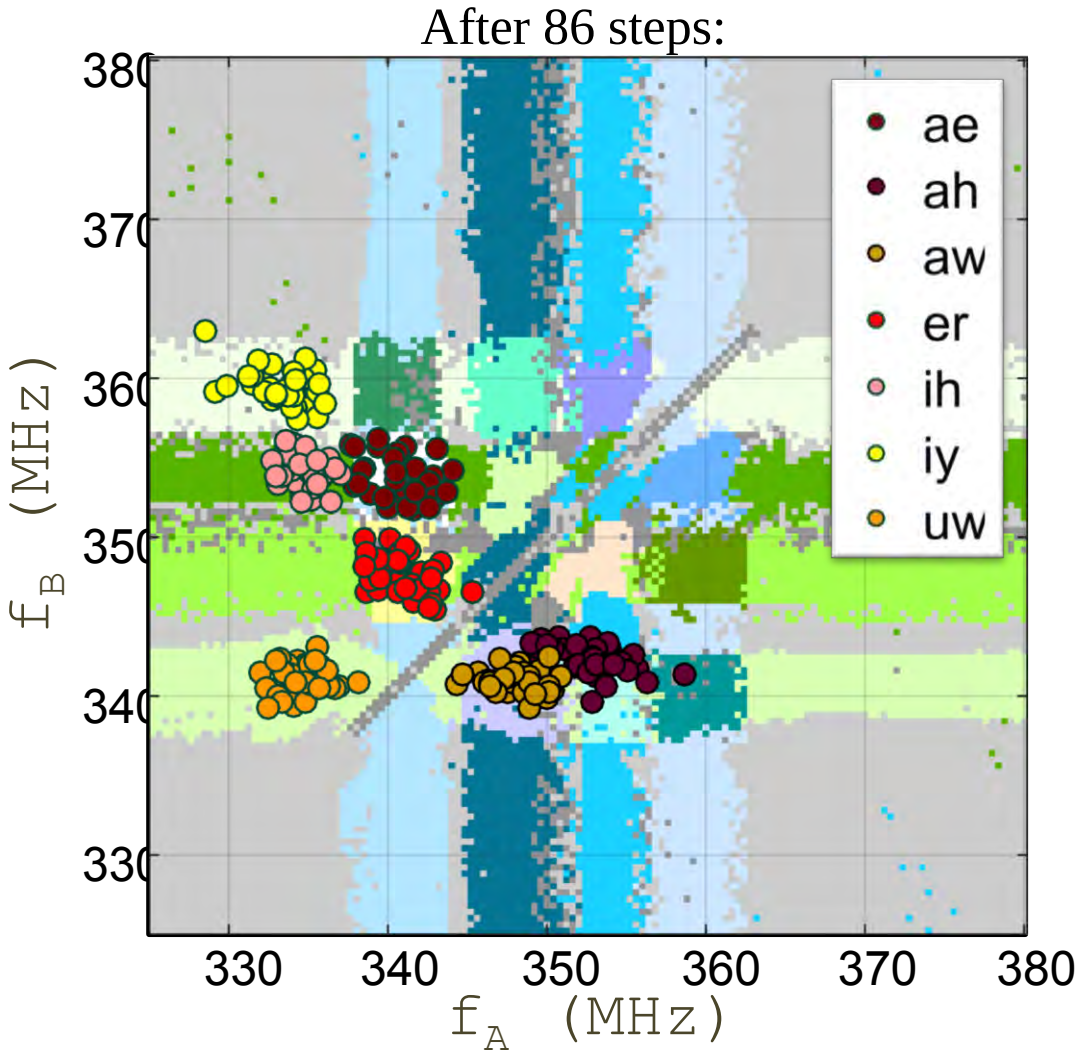

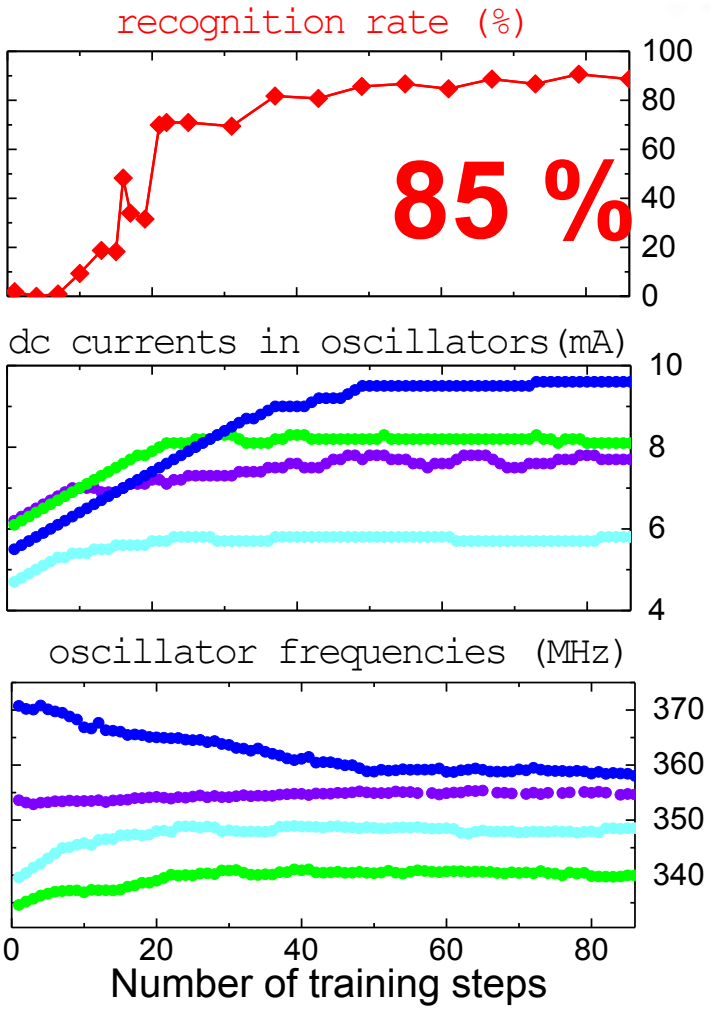

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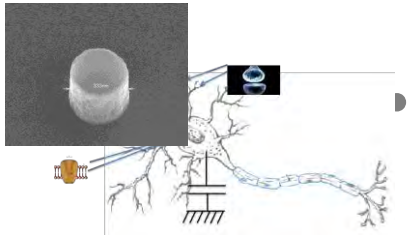
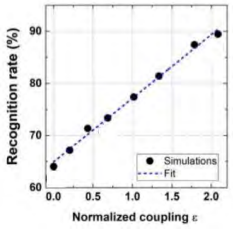
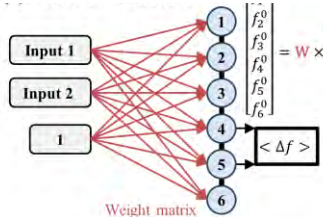


- Can We Use Coupled Dynamical Devices for Computation?



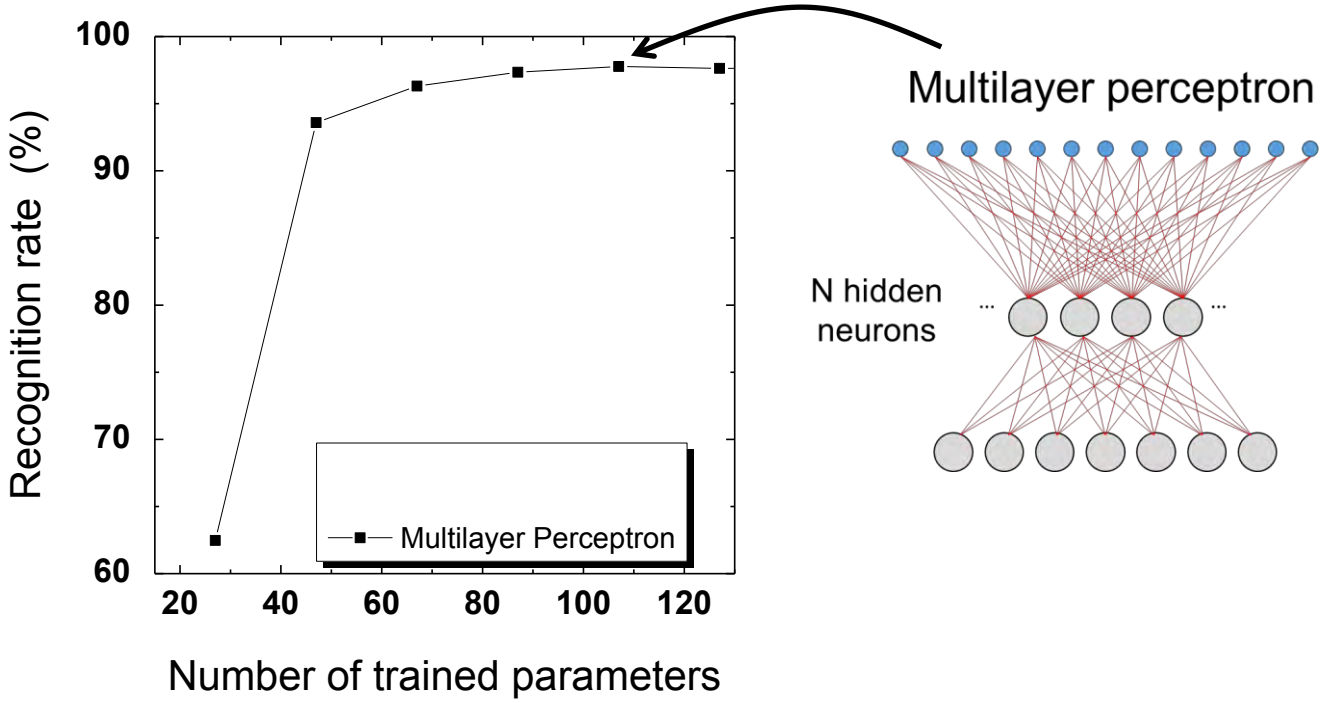
- Why Is It Working?



- Can We Use Concepts from AI with Nanooscillators?

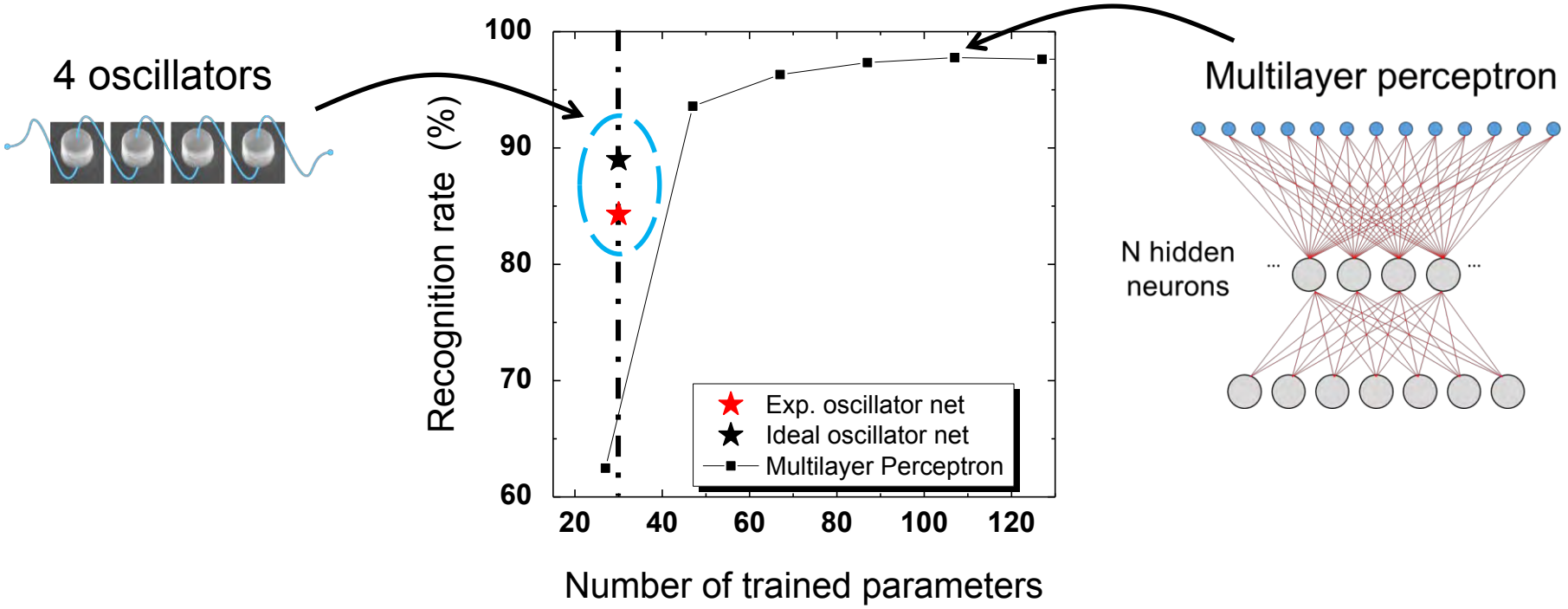
Is Classifying Vowels a Hard Task?

- For benchmarking, we trained a conventional multilayer perceptron on the same dataset



M. Romera, P. Talatchian et al, arXiv:1711.02704

Our Experiments Achieves Higher Recognition Rates than Conventional ANNs with Same Number of Parameters



More physics helps!

M. Romera, P. Talatchian et al, arXiv:1711.02704

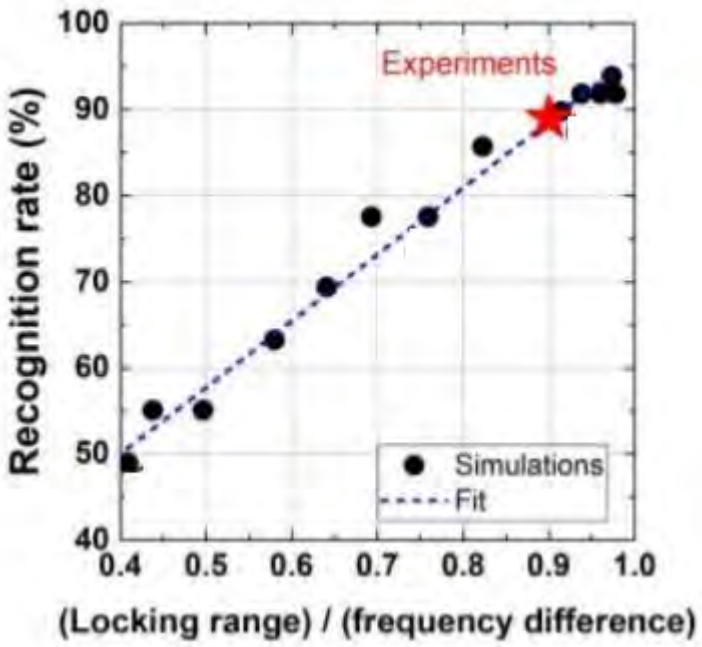
Why Is this Intriguing?

- Based on conventional EE thinking, our system should not really be working

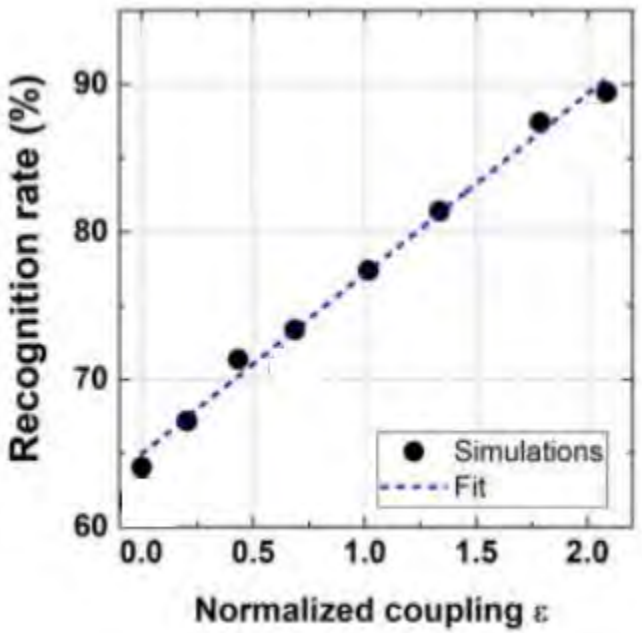
- *Entirely analog*
- *Terrible device variability and phase noise*

What Is Important for Our System to Work?

Device Tunability

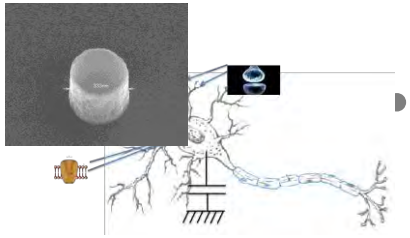


Device Coupling



M. Romera, P. Talatchian et al, arXiv:1711.02704 ; Vodenicarevic et al, Sci Rep 2017

Bioinspired Computing Leveraging the Non-Linearity of Magnetic Nano-Oscillators



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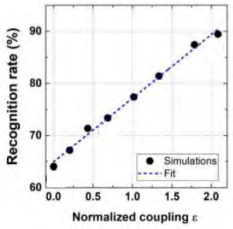

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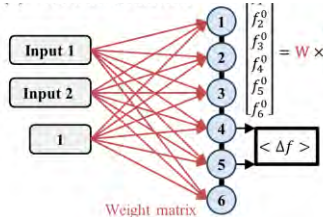
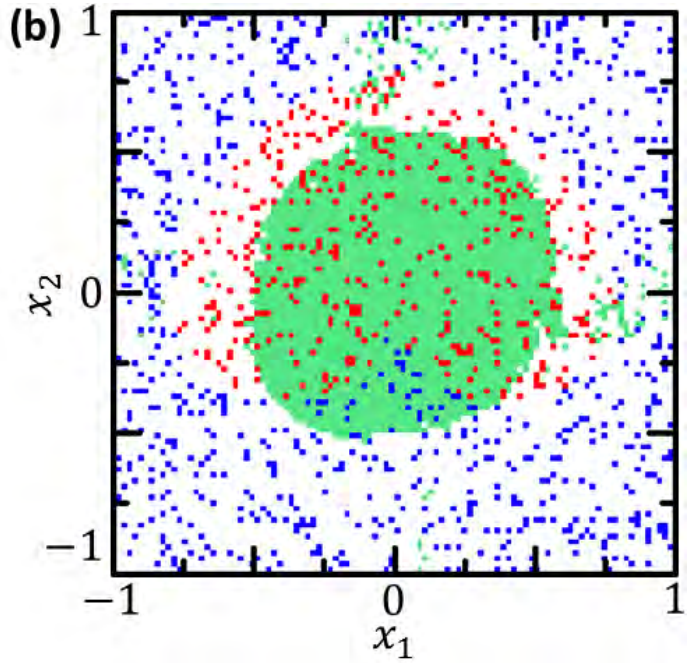


- Can We Use Concepts from AI with Nanooscillators?

Is our Architecture Generic?

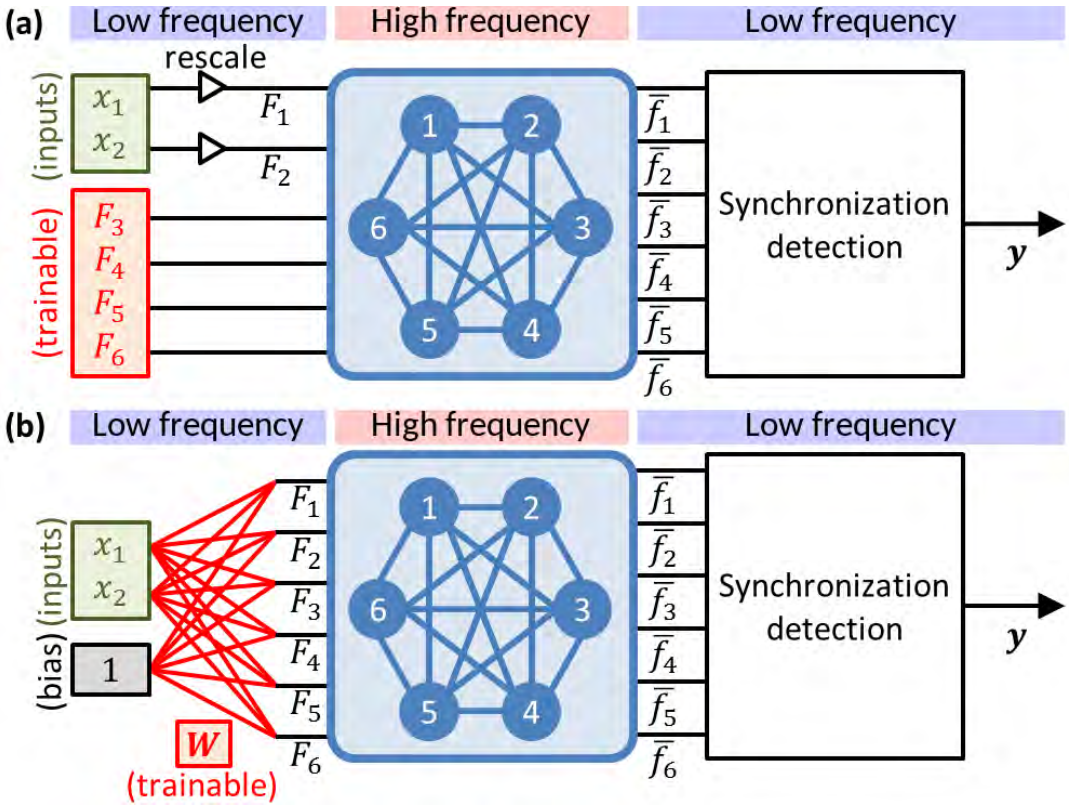
- Not everything can be learned with our architecture

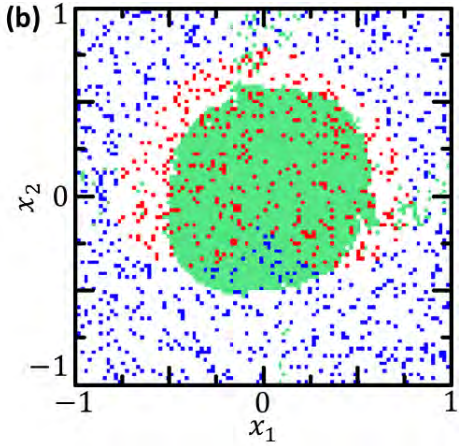


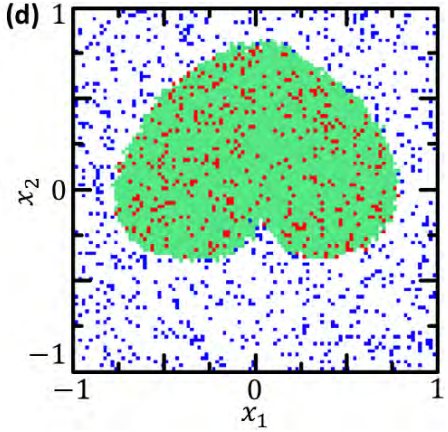
Task
Synchronization pattern of 2 oscillators (green) should match red examples

D. Vodenicarevic et al, J. Appl. Phys., 2018

Generalized Architecture







D. Vodenicarevic et al, J. Appl. Phys., 2018

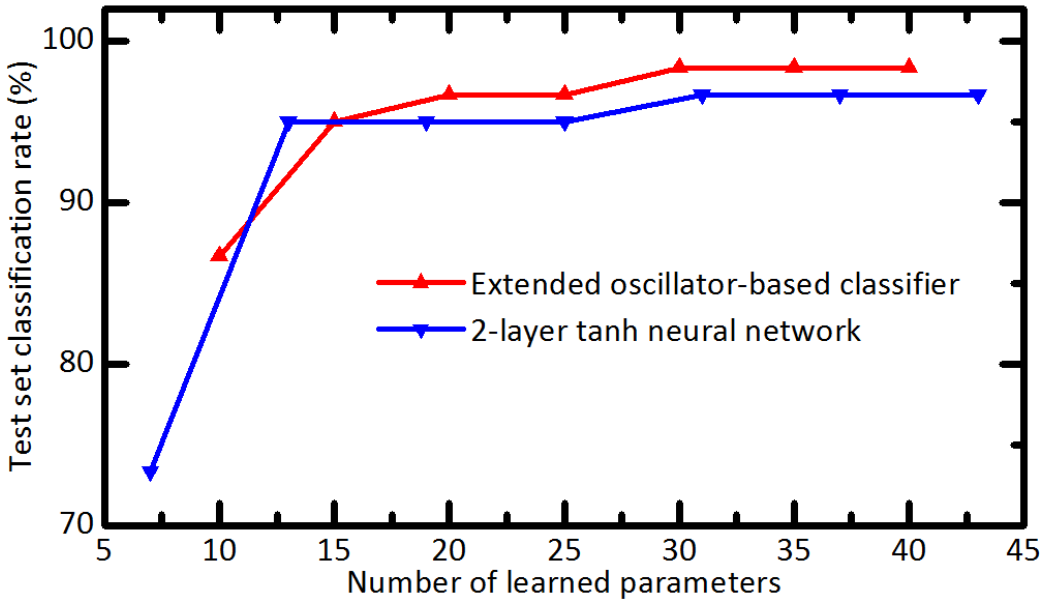
Training the Generalized Architecture

- For the training (optimizing W), can we get at same time benefits of dynamical neurons + power of deep learning techniques?
- We tried a brute force approach
  - Take the differential equations of our system
  - Put them in a deep learning framlework (Tensorflow by Google)

Benchmark on a Simple Machine Learning Task

Iris-setosa *Iris-versicolor* *Iris-virginica*





Works, but slow learning!

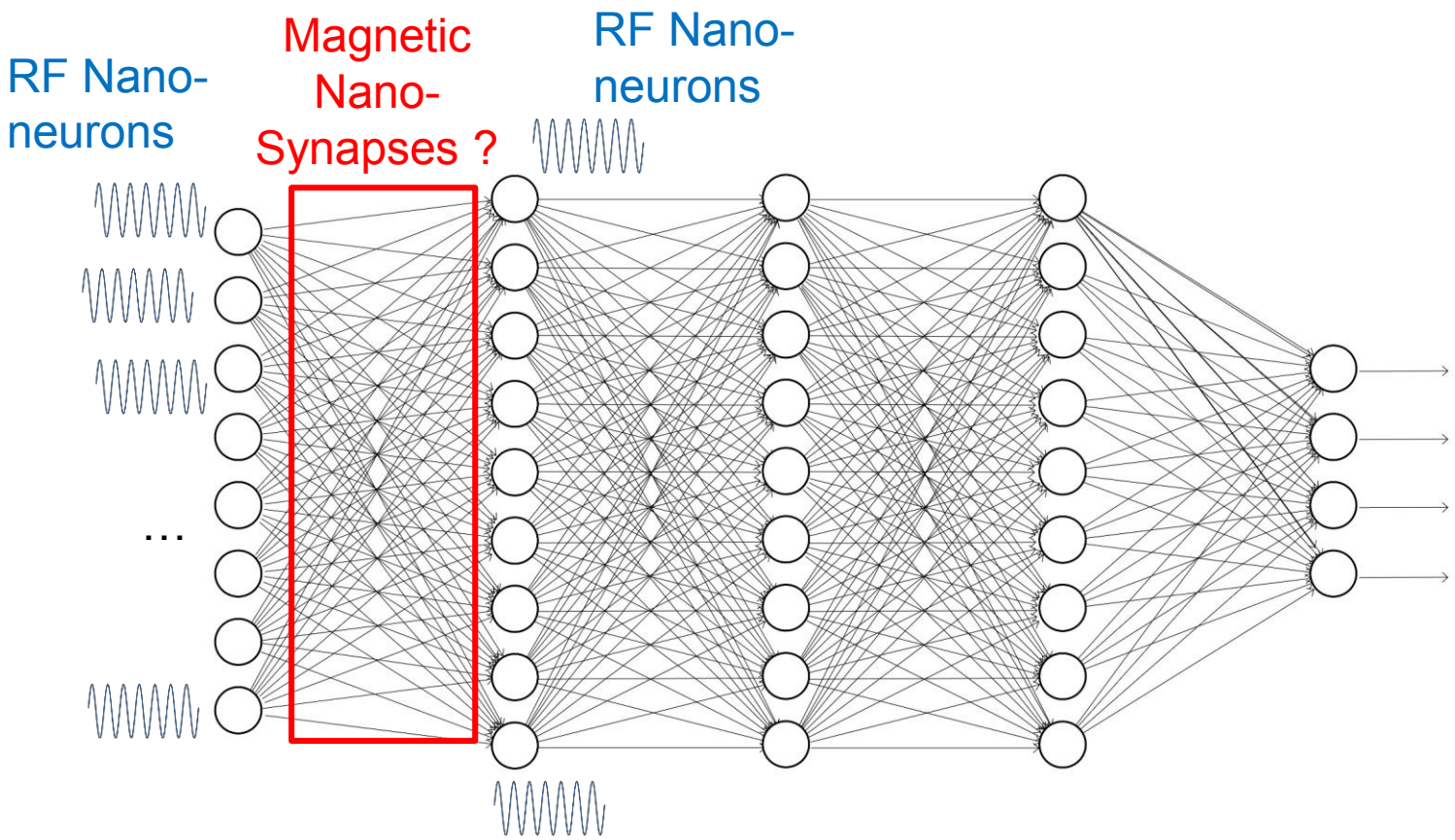
D. Vodenicarevic et al, J. Appl. Phys., 2018

Going Further

- The architecture scales (D. Vodenicarevic, Sci Rep 2017) but training it is difficult

- Future: Going toward multilayer architecture
- Work on coupling mechanisms and detection schemes
- Use on dynamical data

Perspectives: Deep Learning with Spintronic Nanodevice ?



Conclusions

- Exploiting the dynamical behavior of nanoelectronics devices to perform complicated computation works!
- This form of computation is closer to how the brain uses its own devices
- Tunability of devices and their capability to synchronize and to couple to each other are critical
- Possibility to import AI concepts, but the most exciting propsects could come from designing the whole system from scratch

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Thank you for your attention!