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Solving the Travelling Salesman Problem in Continuous Phase Domain with Neuromorphic Oscillatory Neural Networks



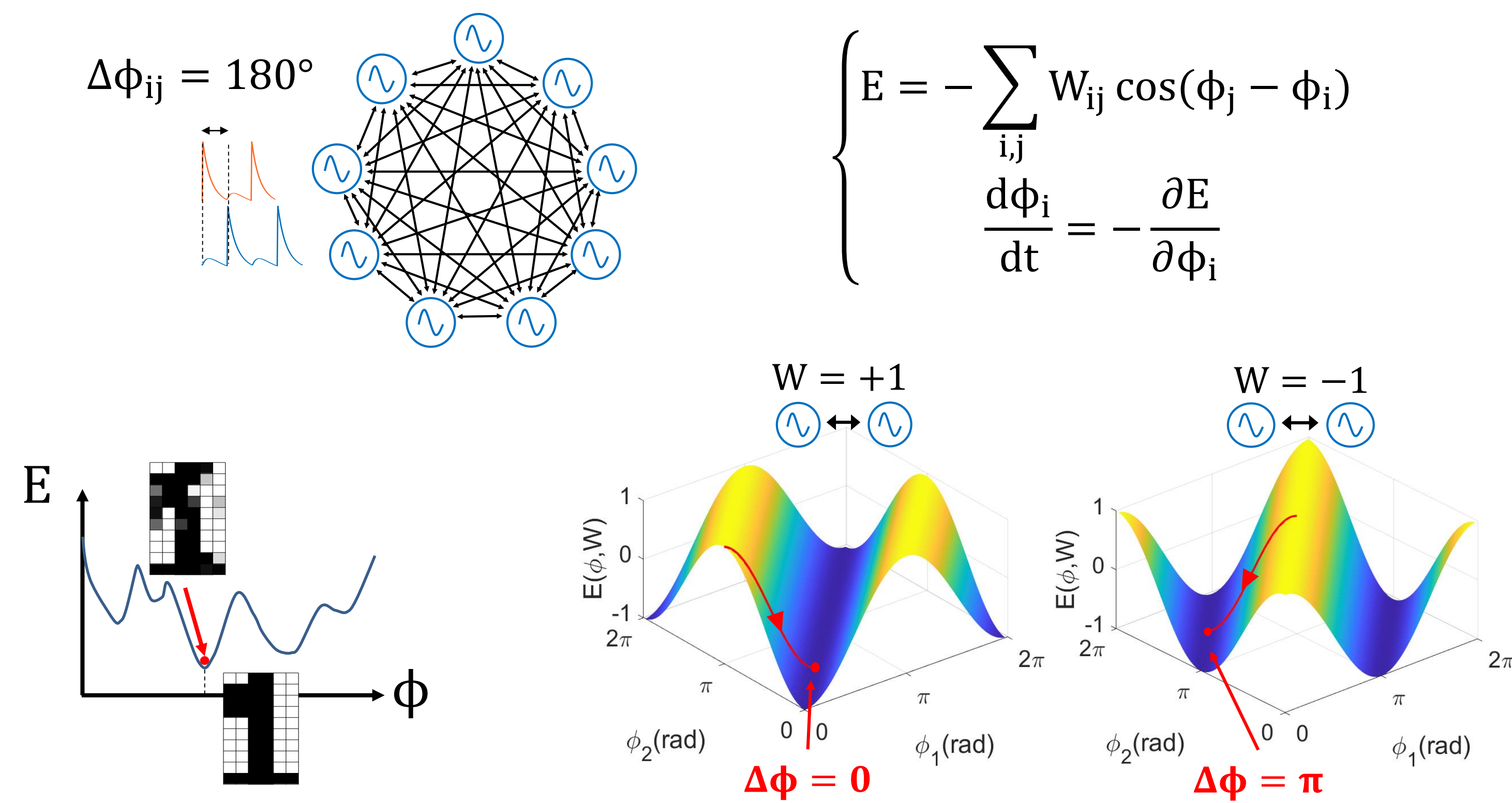
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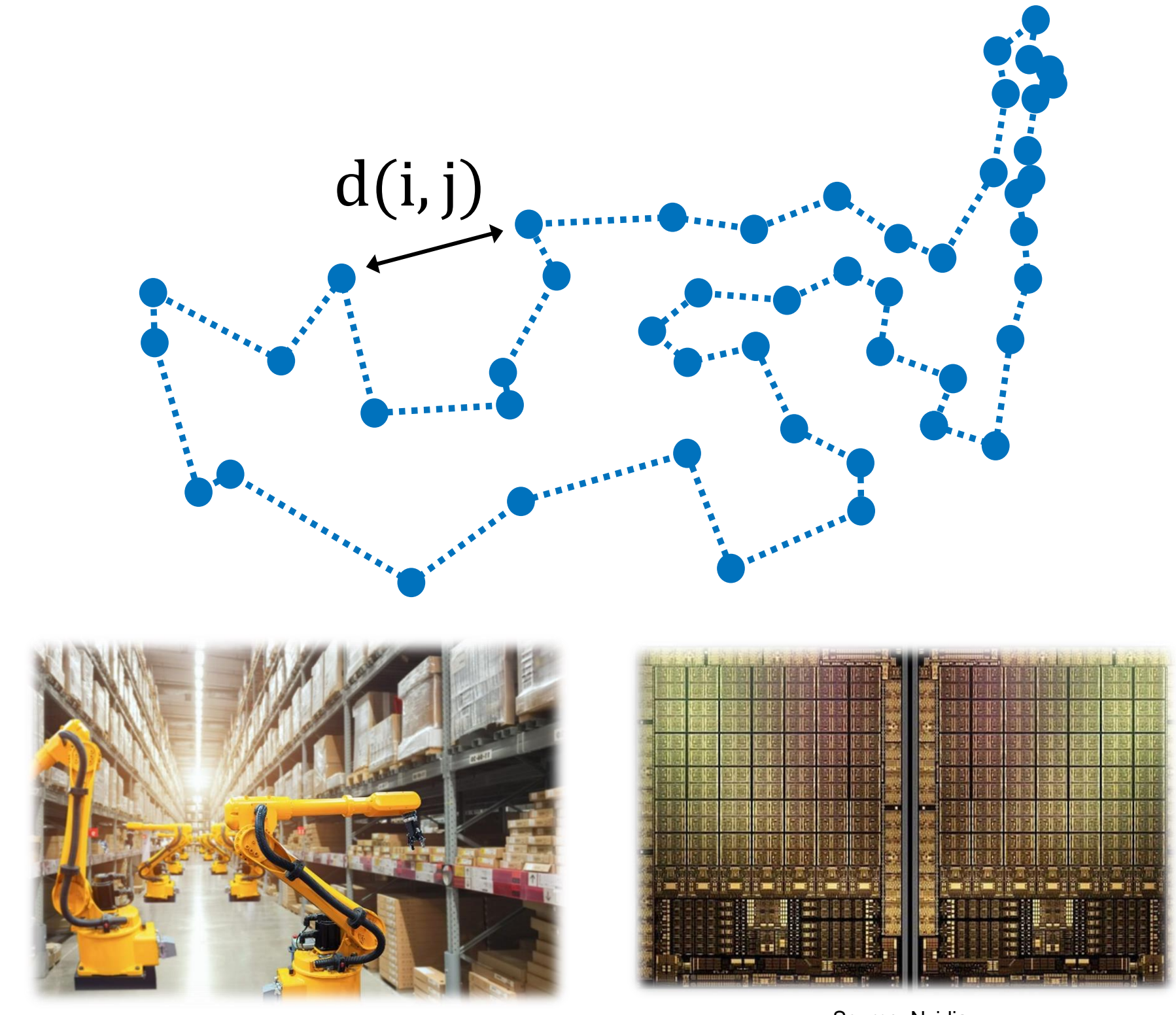
OSCILLATORY NEURAL NETWORKS

- ONNs dynamics are driven by an energy function
- Training the ONN consists in shaping the energy landscape
- ONNs can solve Ising problems or image processing tasks in robotics [1,2,3]



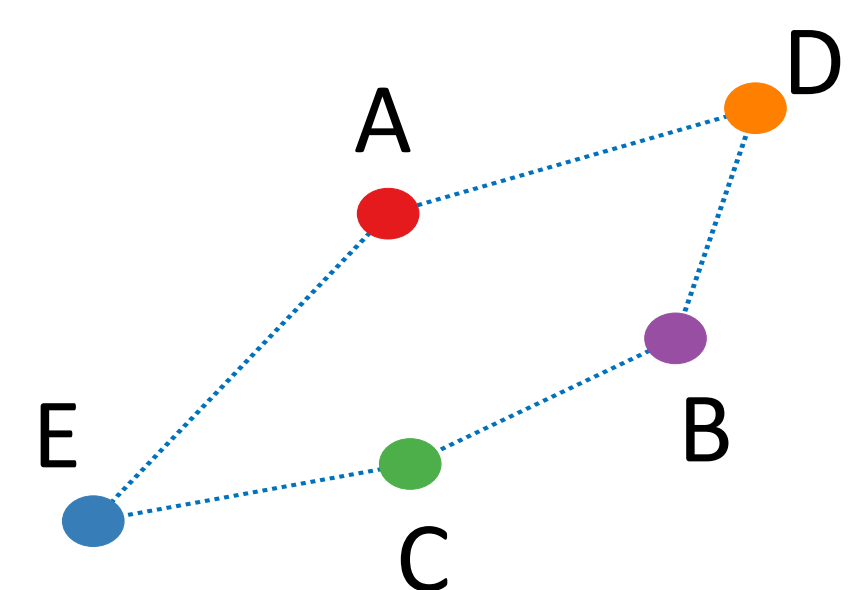
THE TRAVELLING SALESMAN PROBLEM

- Given a list of cities and their inter distances $d(i, j)$, find the shortest tour that visits each city only once
- Solving TSP is NP-hard: $(N - 1)!/2$ possible solutions
- State-of-the-art: 3/2 approximation algorithm from Christofides [4]
- Many applications such as Machine scheduling, warehouse pickup, VLSI routing...



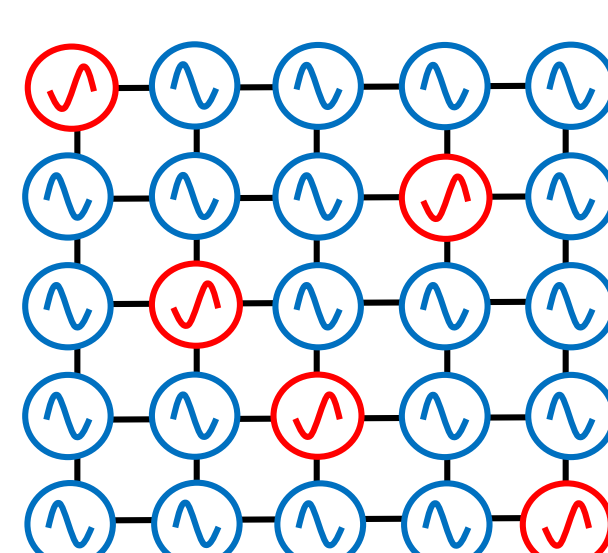
SOLVING TSP WITH ONN

WITH BINARY PHASES (ISING)

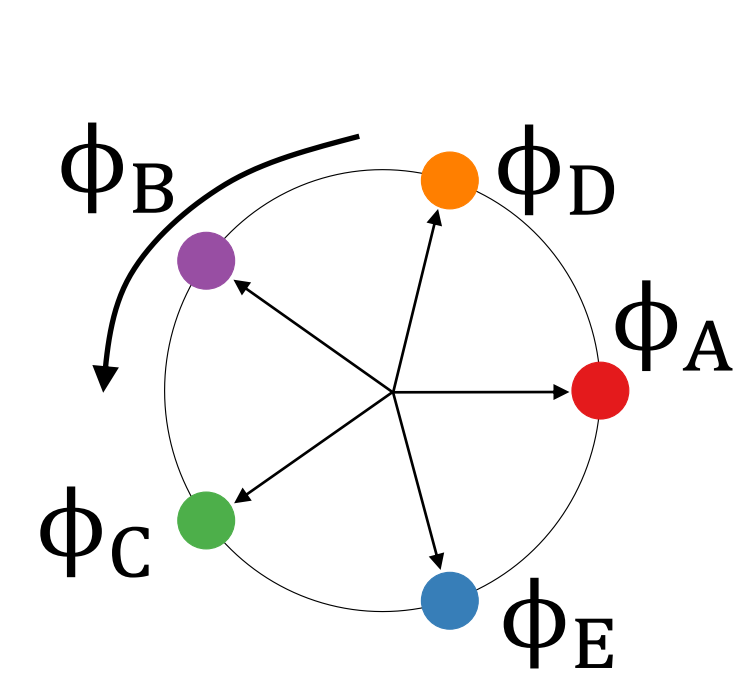
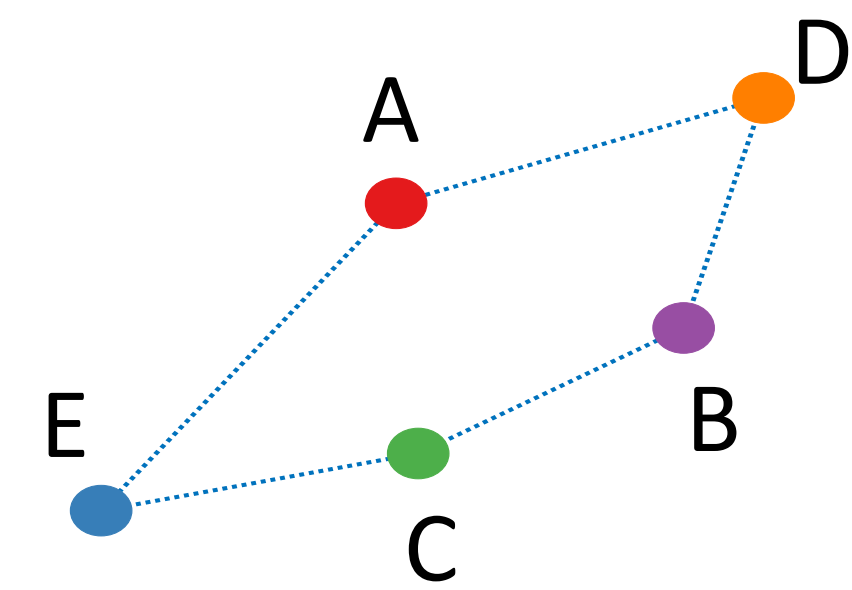


	A	B	C	D	E
P ₁	1	0	0	0	0
P ₂	0	0	0	1	0
P ₃	0	1	0	0	0
P ₄	0	0	1	0	0
P ₅	0	0	0	0	1

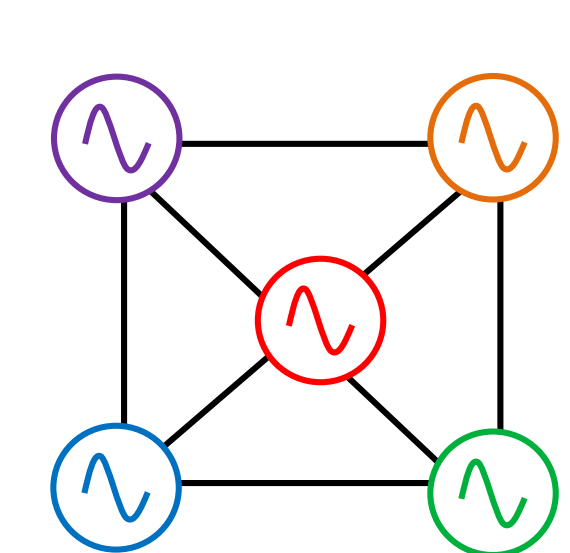
N^2 oscillators



WITH CONTINUOUS PHASES



N oscillators

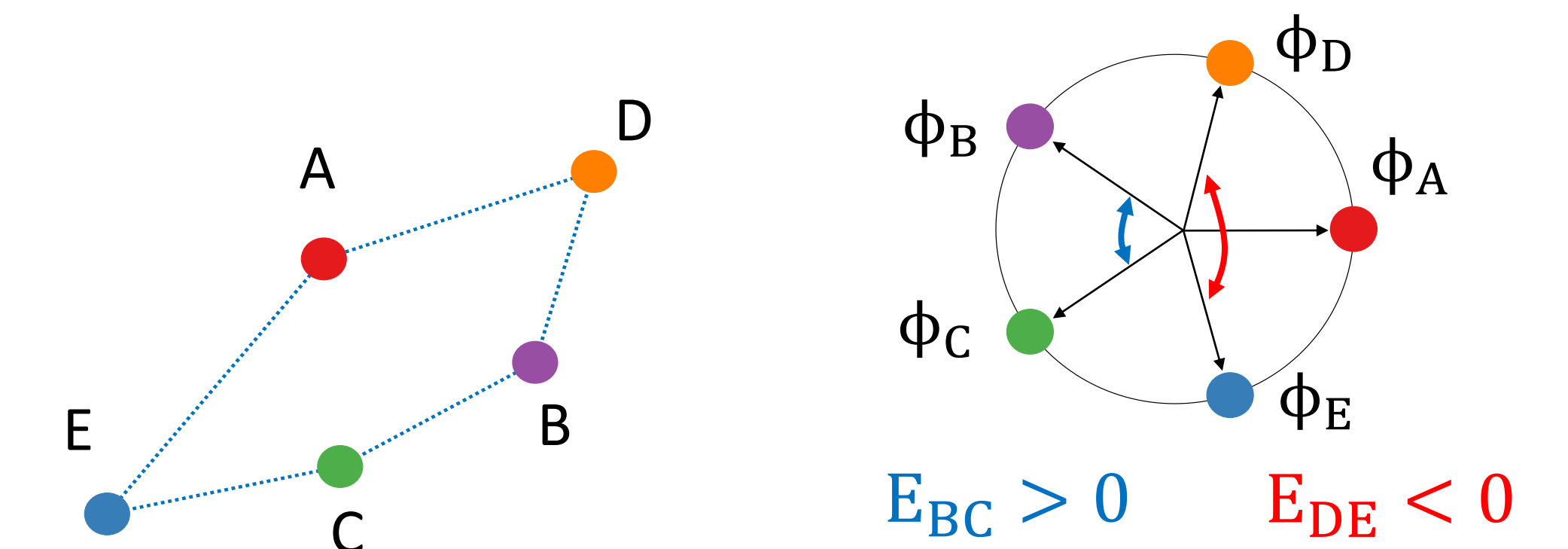


ONN ENERGY FUNCTION AND TSP

- With negative coupling coefficients encoding distances, the ONN « pushes » **all possible phases** apart to minimize E
- Energy terms can be classified in two subsets:
 - $E_{\leq 0} = d_{ij} \cos(\phi_j - \phi_i) \leq 0$
 - $E_{> 0} = d_{ij} \cos(\phi_j - \phi_i) > 0$
- ONN prioritizes cities with long distances ($E_{\leq 0}$) and **minimizes distances between adjacent cities ($E_{> 0}$)**, i.e. the TSP tour

$$W_{ij} = -d_{ij}$$

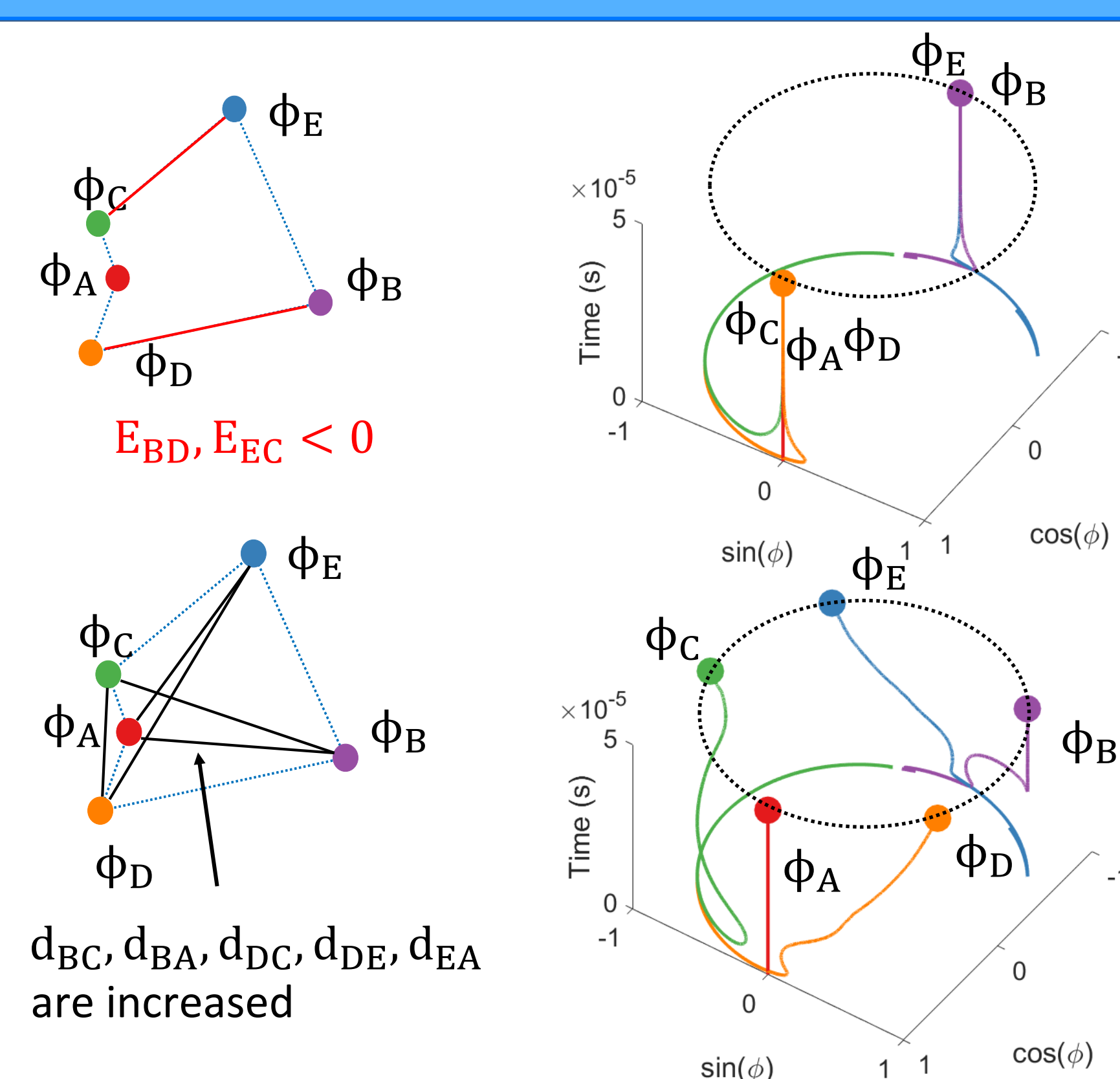
$$\rightarrow E = \sum_{i,j} d_{ij} \cos(\phi_j - \phi_i)$$



SHAPING THE ONN ENERGY LANDSCAPE

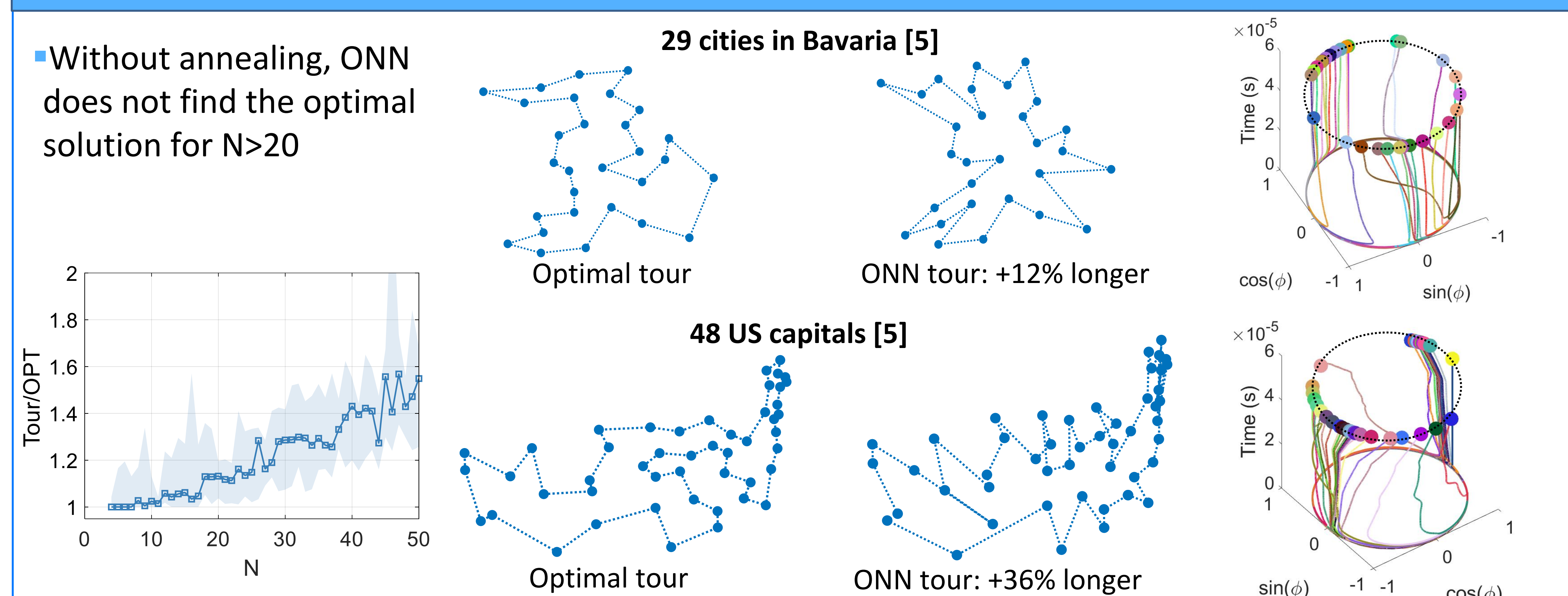
- ONN needs more constraints to better estimate the TSP tour
- Unconstrained, some pairs of adjacent cities can negatively contribute to the total tour distance ($E_{\leq 0}$)
- To mitigate this issue, we shape in real-time the energy landscape as:

If $\Delta\phi_{ij} > \frac{2\pi}{N}$
Increase $|d_{ij}|$ for non adjacent cities (which do not contribute to the final tour)



RESULTS

- Without annealing, ONN does not find the optimal solution for $N > 20$



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- [3] M. Abernot et. al., "Digital Implementation of Oscillatory Neural Network for Image Recognition Applications", Front. In Neuroscience, 2021
- [4] N. Christofides, "Worst-case analysis of a new heuristic for the travelling salesman problem", Report 388, Graduate School of Industrial Administration, CMU, 1976
- [5] TSPLib, <https://www.math.uwaterloo.ca/tsp/data/index.html>, 2009

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