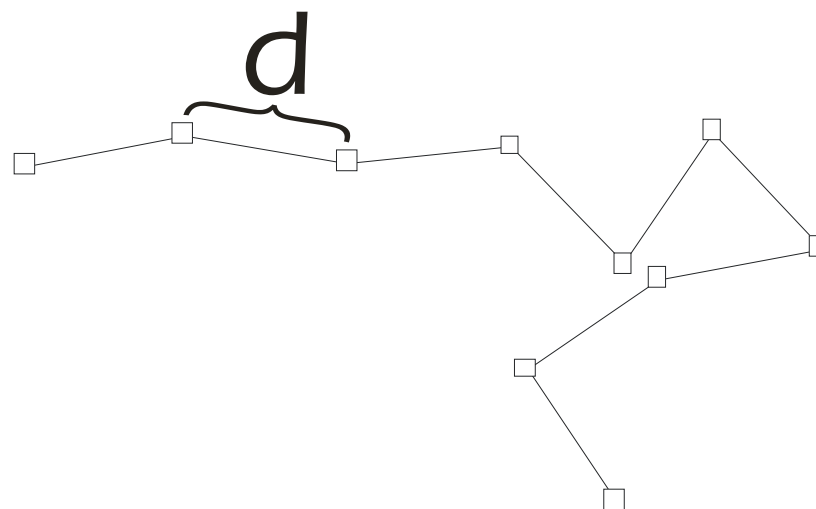


The basic algorithm

- Repeat until convergence:
 1. Select a random trajectory from the repertoire
 2. Make a random change to this repertoire
 3. Check whether total distance increases
 4. If yes, keep change

Trajectories

- Points on a trajectory are equidistant, but can have any angle with respect to each other
- Normally, trajectories have 20 points
- Trajectories exist in a square 2-D space of $15d$ by $15d$

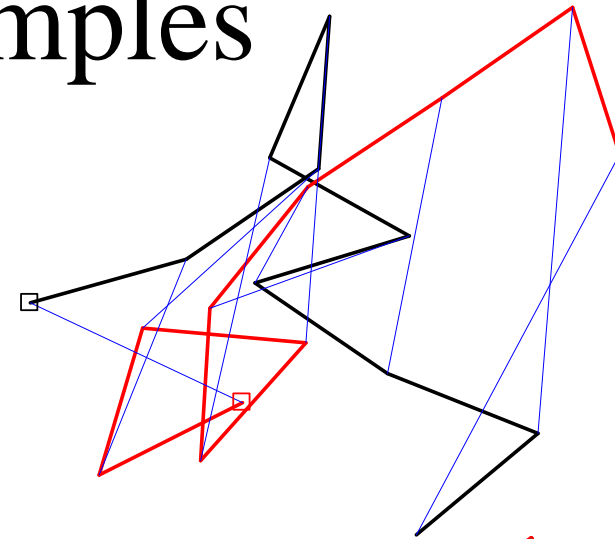
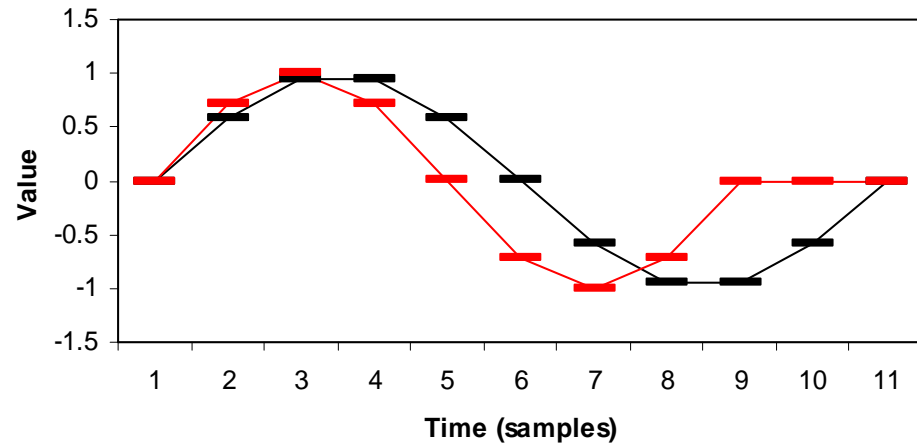


Distance between trajectories

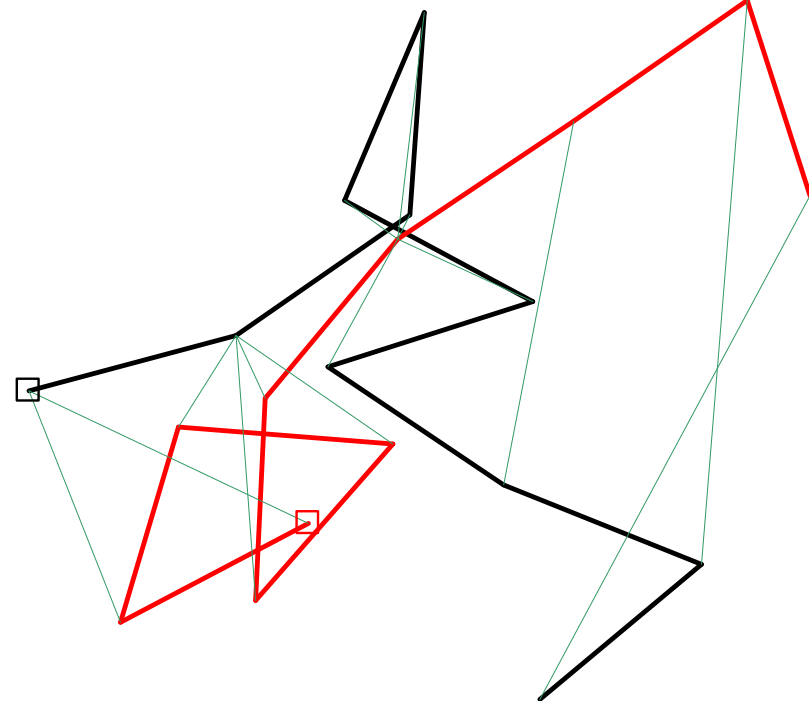
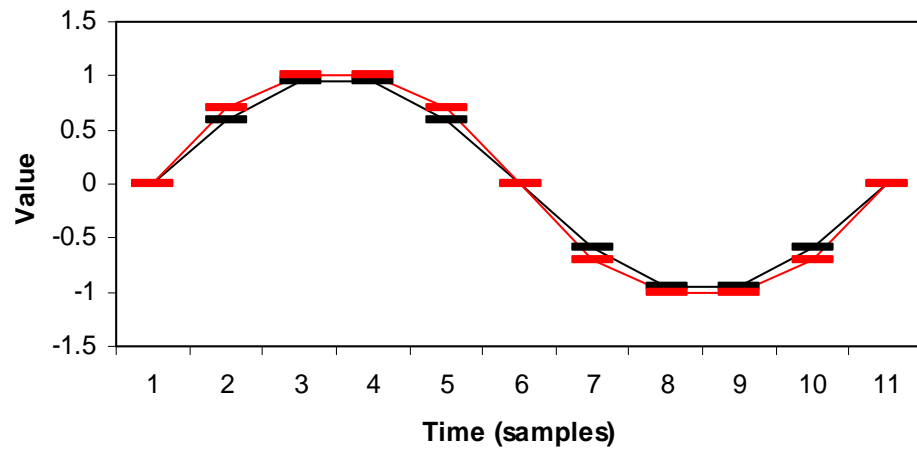
- Distance is not the ordinary Euclidean distance, but the Dynamic-Time-Warped distance
- Formerly used in speech recognition
 - Cognitively plausible
- Ignores small differences in timing between trajectories

DTW-examples

Unwarped comparison, distance squared = 2.4



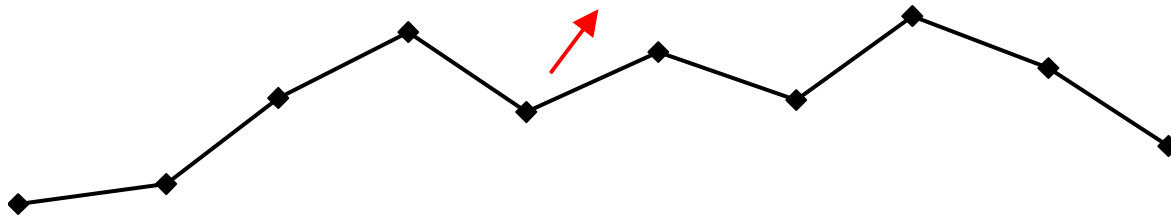
Warped comparison, distance squared = 0.07



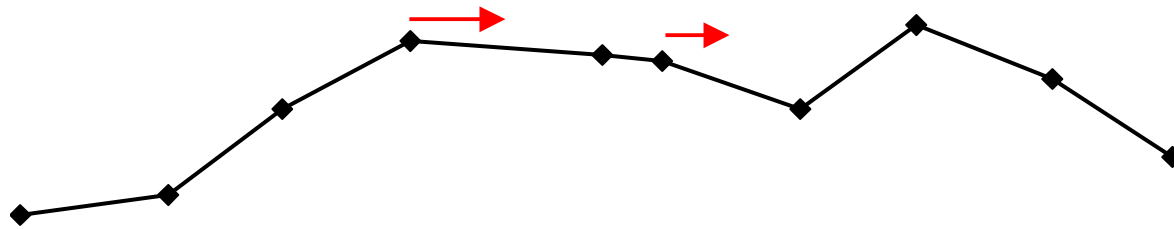
Shifting a trajectory

- Randomly select a point and shift it over a random vector
- Iteratively shift preceding and following points on trajectory in the direction of neighboring points

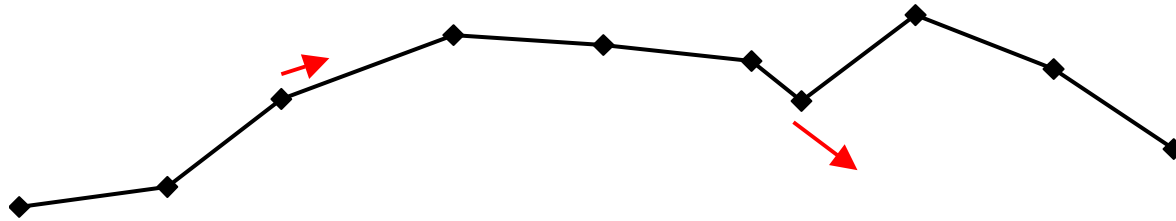
Shifting-example (1)



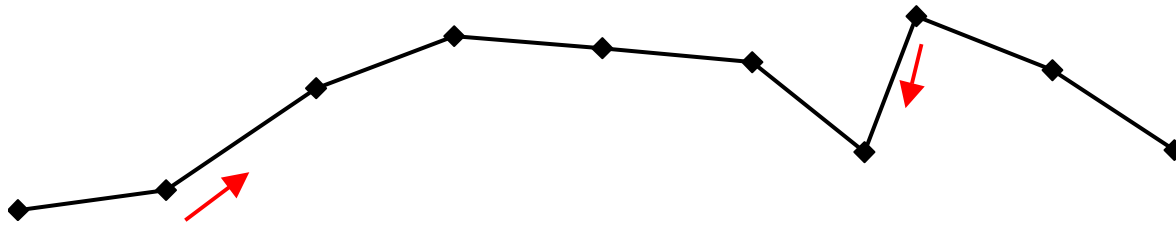
Shifting-example (2)



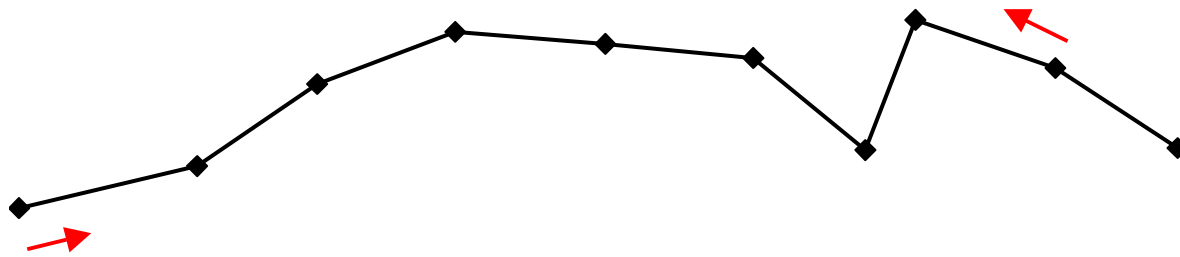
Shifting-example (3)



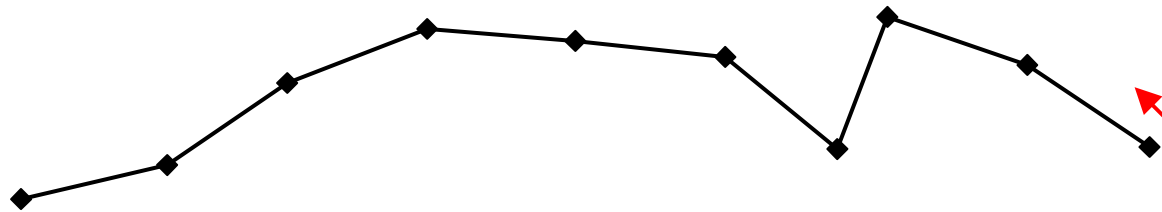
Shifting-example (4)



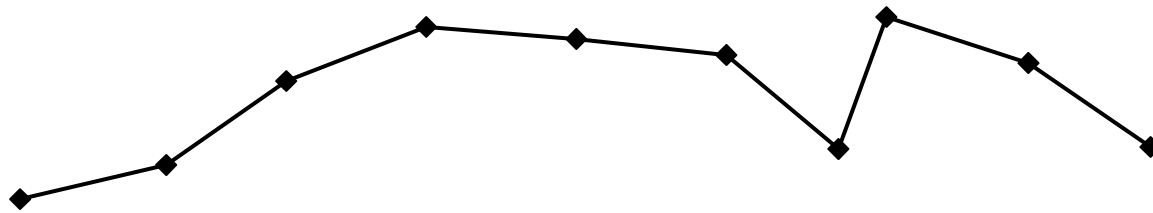
Shifting-example (5)



Shifting-example (6)

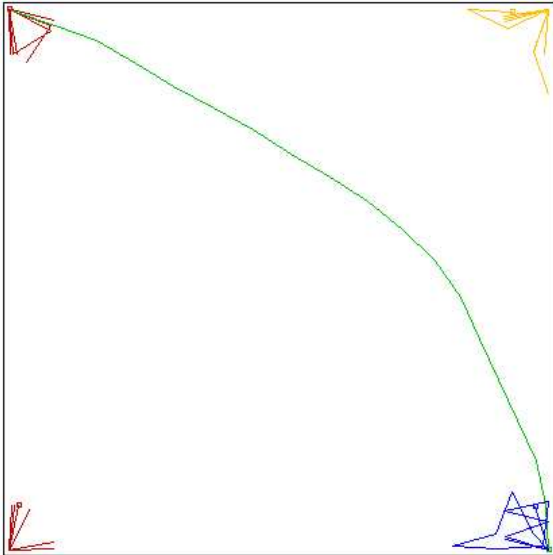


Shifting-example (7)

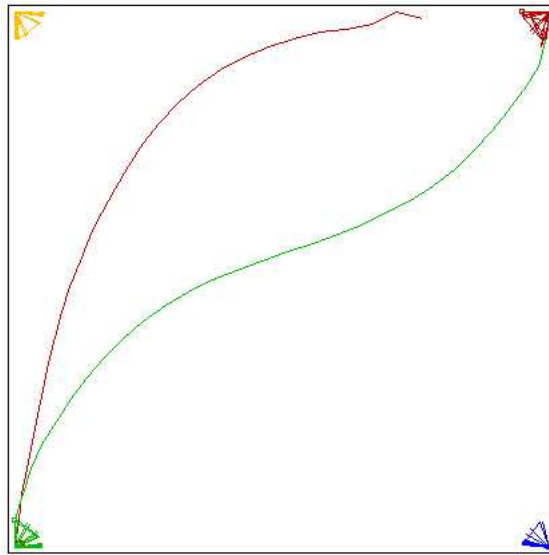


Results

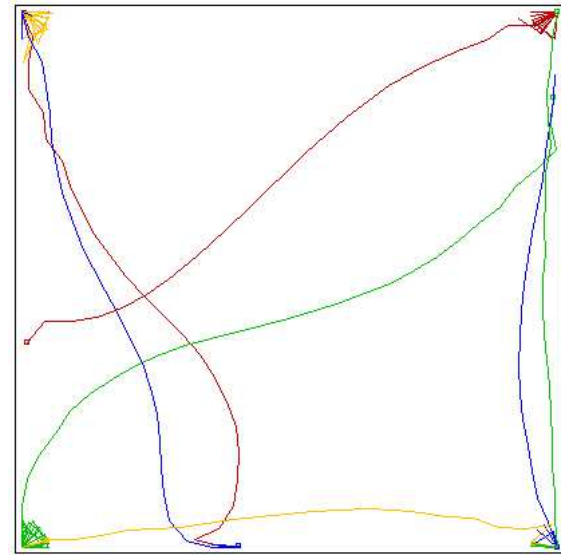
5



6



10



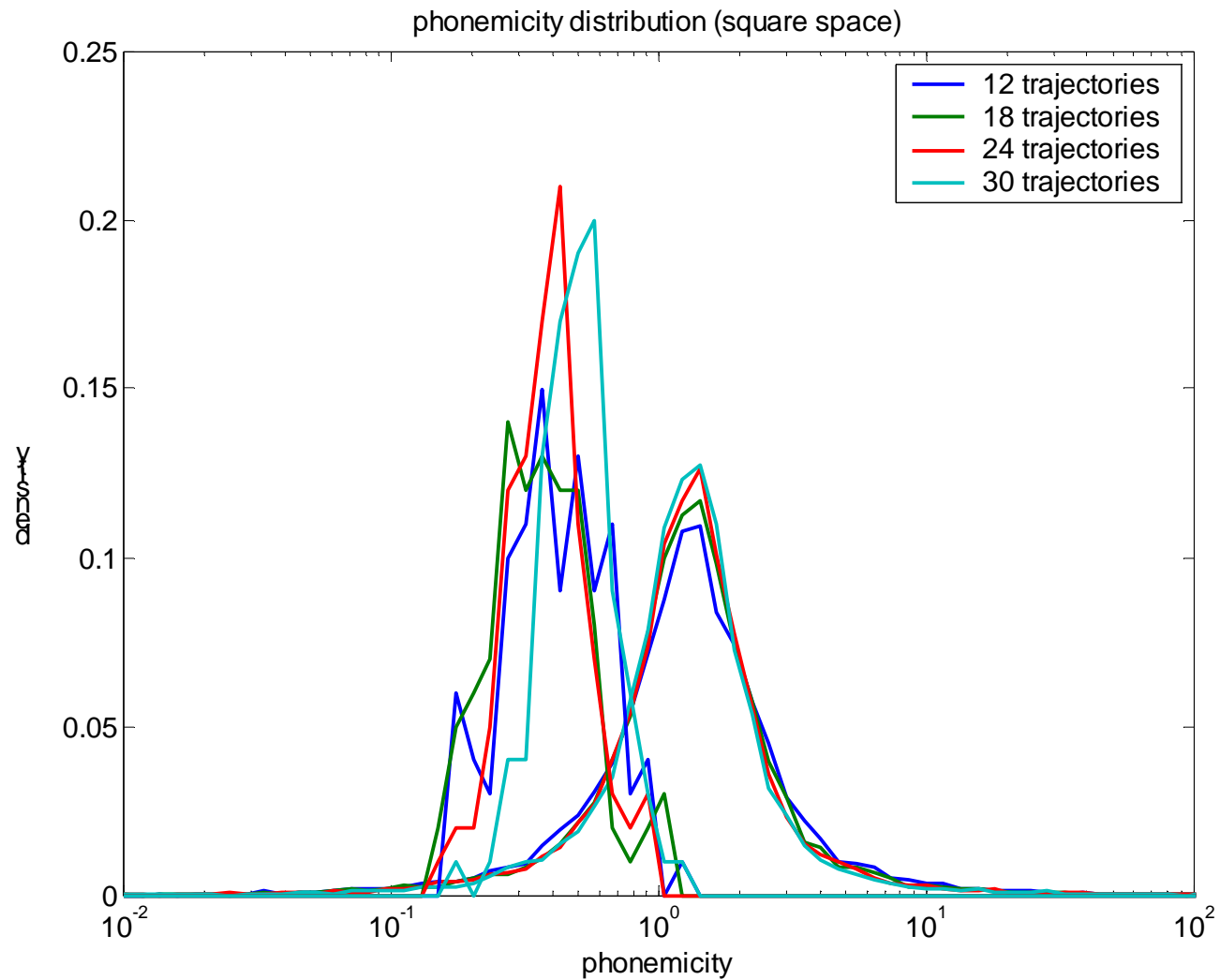
Measuring phonemicity

$$\mathcal{E} = \frac{1}{2N(N-1)} \sum_{i=0}^N \sum_{j=i+1}^N (D(i_1, j_1) + D(i_1, j_L) + D(i_L, j_1) + D(i_L, j_L))$$

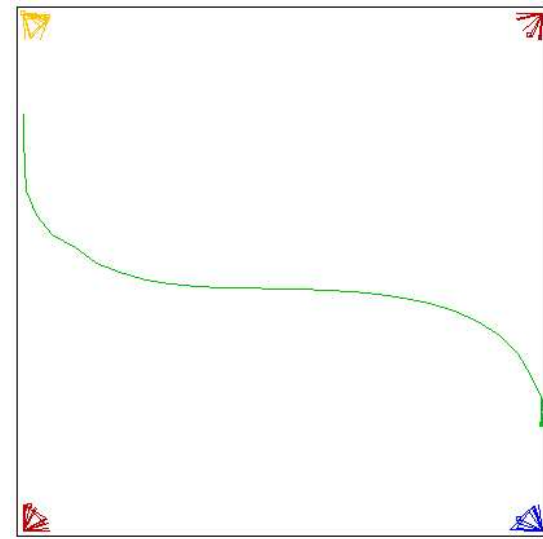
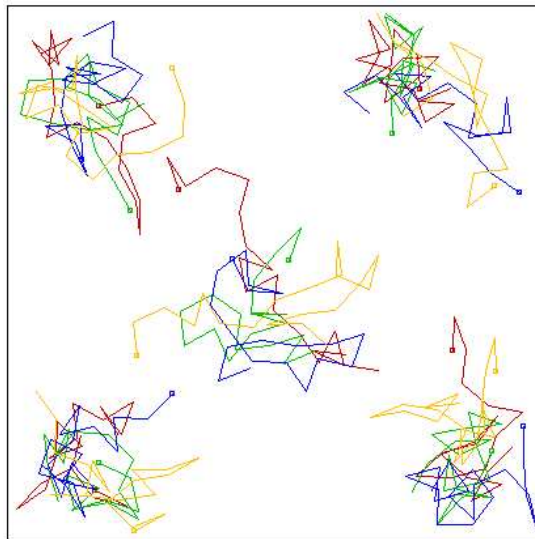
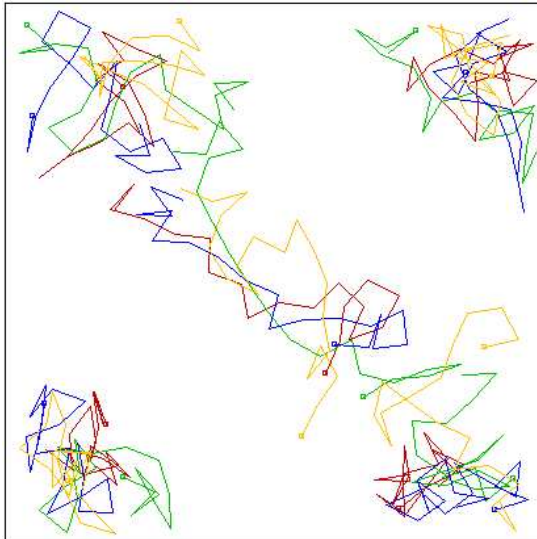
$$\mathcal{C} = \frac{1}{N(N-1)(L-2)} \sum_{i=0}^N \sum_{j=i+1}^N \sum_{k=2}^{L-1} (D(i_k, j_k) + D(i_{L-k+1}, j_k))$$

$$\mathcal{P} = \frac{\mathcal{E}}{\mathcal{C}}$$

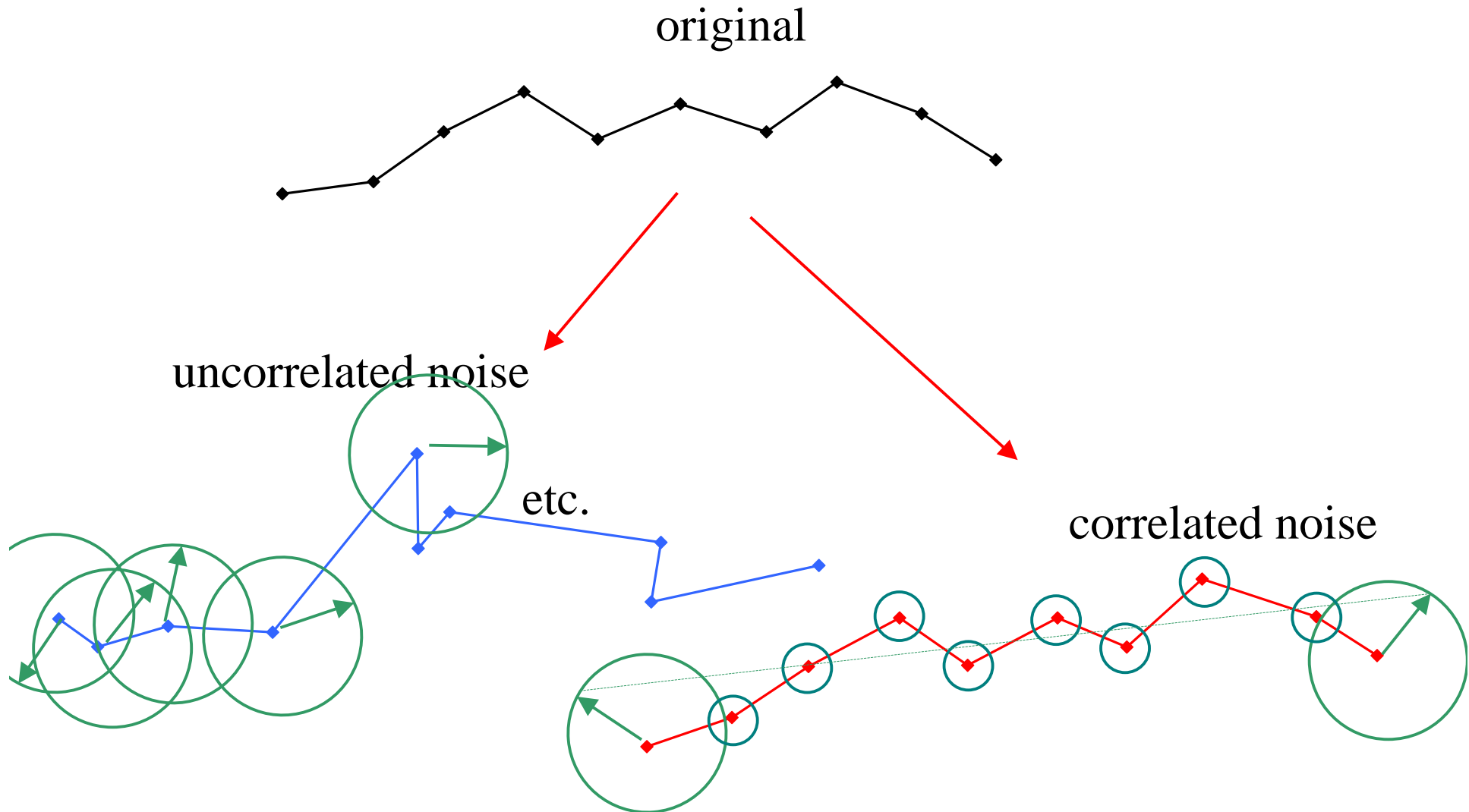
Random vs. optimal



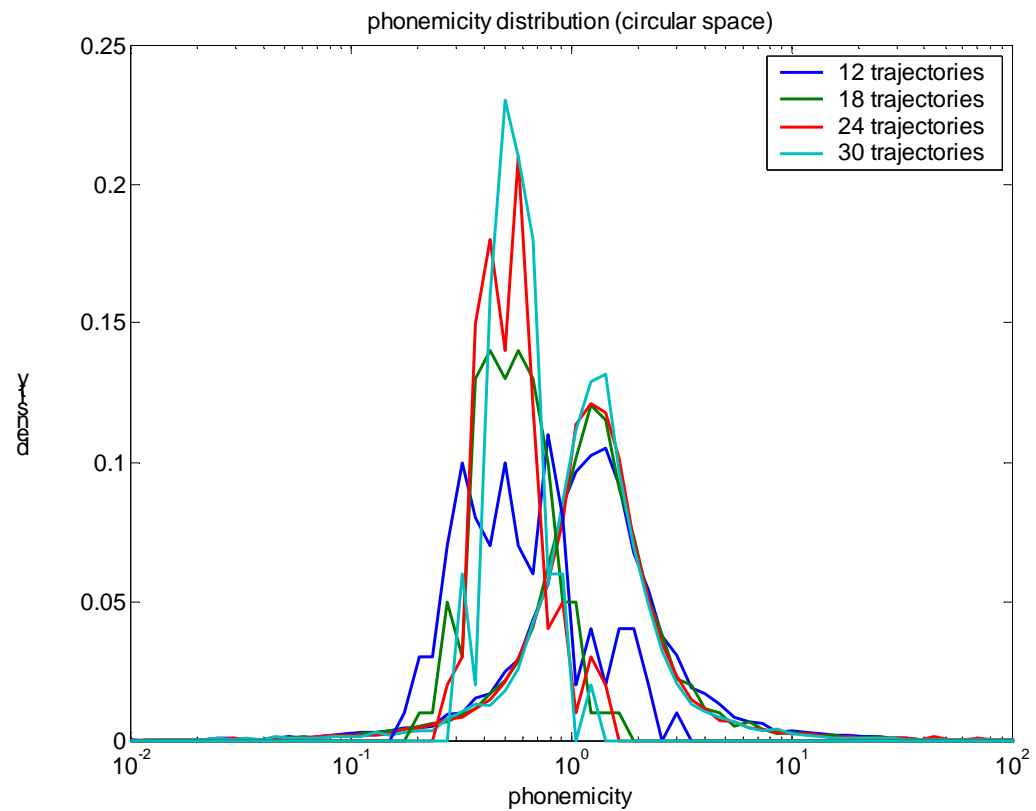
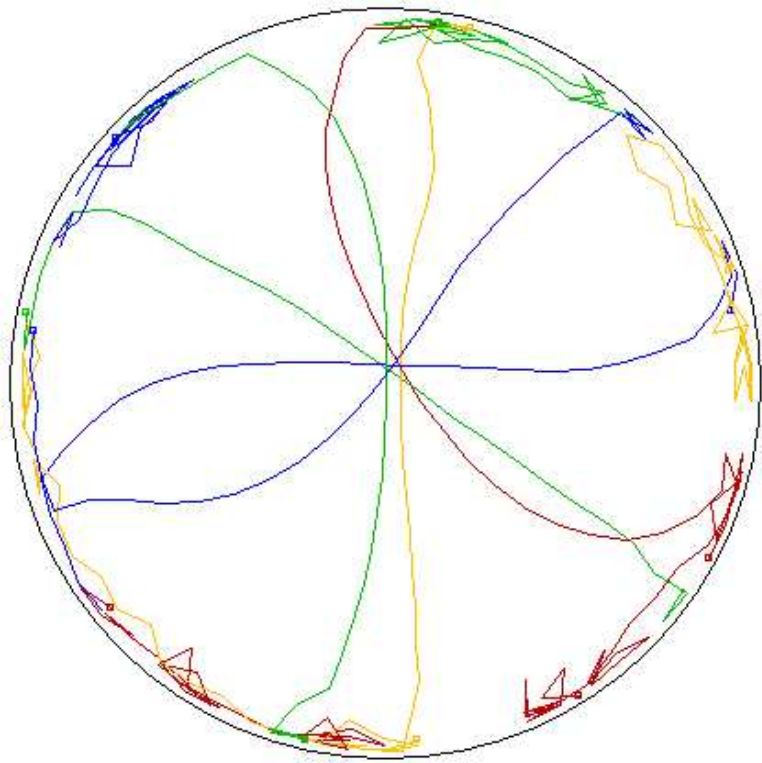
Optimisation and population



Noise conditions



Are corners necessary?



Conclusions

- Phonemic coding emerges when optimizing for distance between trajectories
- Agents do not know this
 - But could start using this later on
 - Work on discovering phonemic coding in progress