Particle Methods Homework 5 – Metehan Dündar

A) Project 1: Multi-Level Image Segmentation via Particle Swarm Optimization (PSO)

- **Paper:** Ma & Hu (2024), "An improved particle swarm optimization for multilevel thresholding medical image segmentation", PLOS ONE. The authors introduce a complementary-inertia-weight PSO (CIWP-PSO) that finds optimal intensity thresholds for segmenting high-bit-depth medical images, using Kapur's entropy as the fitness function.
- **Summary:** The goal is to segment grayscale images by finding multiple threshold values that best separate regions. Traditional exhaustive search is costly for multi-threshold segmentation, especially on high-bit-depth (12-bit) images. Ma & Hu propose a three-layer PSO swarm: particles representing candidate threshold sets are evolved to maximize Kapur entropy. They introduce a layered swarm structure (so poorly performing particles are "refreshed") and use two complementary inertia weights (one increasing, one decreasing with particle age) to balance exploration vs. exploitation. The paper reports that CIWP-PSO finds higher-quality thresholds (measured by entropy and structural similarity) than standard PSO and other methods on MRI datasets.
- **Implementation Plan:** In Python, replicate a simplified version of the algorithm. For example, implement a basic PSO where each particle's position encodes N threshold values for a grayscale image. Define the fitness as the sum of class entropies (Kapur's method). At each iteration:
    - Randomly initialize a swarm of particles (each a sorted list of N thresholds between 0 and 255).
    - Evaluate fitness by applying the thresholds to an image and computing Kapur entropy.
    - Update particle velocities and positions (using standard PSO rules, or include linear inertia weight decay).
    - Re-sample or re-initialize any particles with poor fitness (to mimic the "three-layer" refresh strategy mentioned in the paper).
    - Stop after a fixed number of iterations or when improvement stalls.

  Test this on sample grayscale images (e.g. MRI or natural scenes). Compare the segmentation result to a reference method (like Otsu's multi-thresholding). The output can be the segmented image and plots of entropy vs. iteration.

- **Potential Extensions:**
    - **Vary the objective:** Try using Otsu's between-class variance or cross-entropy instead of Kapur entropy; compare results.
    - **Algorithm variants:** Implement the full CIWP-PSO enhancements: e.g. divide particles into layers by fitness, reinitialize the worst layer with random "opposite" points, or apply a dynamic inertia schedule as in the paper. Evaluate if this improves convergence.
    - **Color or multi-spectral images:** Extend the approach to color image segmentation by thresholding each channel or converting to different color spaces.
    - **Applications:** Apply the PSO-segmentation to a small medical image dataset (e.g. brain MRI slices) to see how segmentation quality (e.g. measured by SSIM or Jaccard index) depends on PSO parameters. Experiment with adding spatial smoothness constraints or merging this with a simple clustering (e.g. PSO for K-means centroids).

Ma J, Hu J (2024) An improved particle swarm optimization for multilevel thresholding medical image segmentation. https://doi.org/10.1371/journal.pone.0306283