A Spectral Hypergraph-Based Framework for Early Detection of Alzheimer's Disease from Multimodal Neuroimaging Data

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1. Executive Summary

This project introduces an advanced spectral hypergraph-based analytical framework to detect early signs of Alzheimer's disease using multimodal neuroimaging data. By representing brain connectivity through hypergraphs rather than traditional pairwise graphs, the proposed method captures complex, higher-order interactions between brain regions across modalities such as EEG, fMRI, and DTI.

2. Scientific Background and Motivation

Alzheimer's disease (AD) is a progressive neurodegenerative disorder with substantial personal and societal costs. Early detection remains a major clinical challenge. Existing graph-based approaches primarily model pairwise correlations, which fail to capture the multifaceted dynamics of the human brain. Hypergraphs provide a mathematically rigorous model to represent higher-order and nonlinear interactions between multiple brain regions, thereby offering a potentially more accurate biomarker for early-stage AD.

3. Methodology

- **Data Acquisition:** Integration of multimodal neuroimaging datasets, including EEG (temporal dynamics), fMRI (functional connectivity), and DTI (structural pathways).
- **Hypergraph Construction:** Brain regions are modeled as nodes. Hyperedges are created by correlating activity patterns across multiple regions using spatiotemporal and cross-modal criteria.
- **Spectral Analysis:** Compute the hypergraph Laplacian matrix. Extract spectral signatures such as eigenvalues, hypergraph entropy, and spectral centrality metrics for use as discriminative features.
- **Machine Learning Pipeline:** Use extracted spectral features for classification via supervised learning (e.g., SVM, neural networks) to distinguish between healthy and AD-affected individuals.

4. Key Innovations

- Models nonlinear, high-order interactions that are overlooked by standard graph-based approaches.
- Extracts advanced spectral features including spectral entropy, Laplacian energy, and hypergraph centrality.
- Fuses heterogeneous data sources into a unified representation of brain connectivity.
- Enables detection of preclinical cognitive dysfunction before structural degradation is evident in MRI scans.

5. Potential Experimental Design

We propose a pilot experiment using 100 subjects from the ADNI database, stratified into cognitively normal, MCI, and early-stage AD groups. For each subject:

- Construct a modality-specific hypergraph and a fused multimodal hypergraph.
- Compute spectral descriptors for each graph.
- Train a classifier on 70% of the data and evaluate accuracy, sensitivity, and specificity on the remaining 30%.

This simulated scenario provides a proof of concept and a basis for scaling up the study.

6. Anticipated Impact

The proposed framework has the potential to significantly enhance early diagnosis of Alzheimer's disease. It may also serve as a foundation for real-time cognitive monitoring systems and aid in the development of preventative interventions.

7. Tools, Frameworks and Datasets

- **Programming Environment:** Python (NumPy, SciPy, PyTorch)
- **Graph Processing:** NetworkX, HyperNetX, or custom spectral hypergraph modules
- **Datasets:**
  - Alzheimer's Disease Neuroimaging Initiative (ADNI): https://adni.loni.usc.edu
  - Human Connectome Project (HCP): https://www.humanconnectome.org

8. Intellectual Property and Licensing