Research Statement

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Introduction

My research focuses on developing mathematical and computational models to address complex, real-world challenges. This work spans multiple disciplines, including decision-making under uncertainty, game theory in competitive environments, synchronization in natural and artificial systems, active learning, fairness in ranking, and resource allocation in machine learning. By employing robust mathematical formulations, my goal is to establish actionable frameworks that enhance both theoretical insight and computational efficiency in these domains.

Previous Research and Contributions

As part of my commitment to developing mathematical and computational models for addressing complex, real-world problems, my research covers a diverse range of fields, including game theory and bandit theory, synchronization in complex networks, interconnection networks, and theoretical machine learning. My key contributions include:

1. Decision-Making in Competitive Multi-Environment Settings

My doctoral dissertation, *Computational Models for Decision Making in Multi-Environments*, analyzed Bayesian Nash equilibria in multi-agent scenarios (*Games, 2018*). This work provides a foundational understanding of decision-making in competitive environments, with practical implications for strategic technology adoption, product portfolio management, and knowledge-sharing strategies. Furthermore, my exploration of *product portfolio management in competitive environments* (*Game Theory Society Congress, 2018*) introduced strategic models for optimal decision-making in economic networks.

2. Synchronization in Complex Networks

Synchronization among networked oscillators is observed across a spectrum of applications—from biological systems and social dynamics to AI-driven distributed computing. My research on Kuramoto networks investigated how structural features affect synchronization, proposing a *rewiring mechanism to improve synchronization in networked oscillators* (*Journal of Statistical Mechanics, 2022*). I also developed *error correction models for Kuramoto oscillators* that enhance synchronization stability (*Applied Mathematics and Computation, 2021*).

3. Scalable Interconnection Networks

Interconnection networks are integral to high-performance computing. I introduced a *Cost-Performance Scalability Measure for Interconnection Networks*, a novel metric for evaluating scalability in computing architectures (*Journal of Interconnection Networks, 2025*). Additionally, I designed the **Overlapped Cube (OCube) topology**, which offers higher fault tolerance and efficiency in multiprocessor systems.

4. AI and Machine Learning: Active Learning and Fairness

Within theoretical machine learning, my work has contributed to *active covering*, a variant of active learning that seeks to optimize data labeling. Specifically, I proposed *Density-Adjusted Learning Algorithms (DANA & DAA)* that improve label efficiency and classification accuracy (*ACM KDD, 2024*), with applications in fraud detection and risk analysis. I have also developed *algorithmic fairness measures* for ranking systems, introducing a *statistical fairness metric* that assesses rankings by their likelihood in an unbiased context (*ACM WWW, 2025*). This metric provides a quantitative foundation for mitigating algorithmic bias.

5. Practical Applications and Collaborations

My research has been successfully applied in:

- **Computational Neuroscience**: Analyzing neuronal synchronization and learning processes in the brain.
- **Biological Cognition**: Designing clinical trials and examining human decision-making behavior.
- **Financial Systems**: Leveraging machine learning techniques for fraud detection, risk assessment, news recommendation, dynamic pricing, and network routing.
- **Multiprocessor Systems**: Developing scalable network architectures.
- **Strategic Decision-Making**: Employing game theory in economic networks, social interactions, and computational psychiatry.

Moreover, I have collaborated with researchers from **Imperial College London, Google, Sharif University of Technology, and the Institute for Research in Fundamental Sciences (IPM)**.

Current Research

Building on these foundations, my current research centers on interconnection networks, decision-making under uncertainty (bandit theory), and budget allocation over unknown value functions. Specifically:

- **Overlapped Network Topologies for Multiprocessor Systems**
  - Developing adaptive network architectures suited for large-scale interconnection networks.
  - Improving fault tolerance and efficiency in multiprocessor systems.
- **Budget Allocation for Unknown Value Functions**
  - Designing objective optimization methods for budget allocation problems.
  - Formulating algorithmic solutions with strong theoretical guarantees to optimize resource distribution.
  - Establishing hardness results that elucidate the computational complexity.
  - Conducting experimental validations to assess real-world performance.

The research on budget allocation for unknown value functions has been submitted to ICML 2025, while the investigation into overlapped network typologies for multiprocessor systems is currently ongoing.

Future Research Directions

Looking ahead, I aim to deepen both the theoretical and practical impact of my work in machine learning, data analysis, and interconnection networks. My long-term objectives include:

1. Decision-Making Under Adversarial Uncertainty

- Developing algorithms for batched adversarial linear bandits.
- Establishing theoretical regret bounds and hardness results to guide computational approaches.

2. Exploring Objective Function Approaches for Budget Allocation Across Diverse Applications

- **Evaluating Intermediate Models in Machine Learning**:
  - Efficiently allocating resources (time, computational power, data) to test multiple models.

- Maximizing performance while minimizing superfluous computation.

- **Balancing Cost and Performance in Decision-Making**:
  - Addressing budget constraints in AI model selection, clinical trials, and industrial production.
  - Crafting resource allocation strategies for optimal outcomes under limited budgets.

- **Enhancing Synchronization in Networked Systems**:
  - Strategically allocating resources to improve synchronization in complex systems.
  - Fostering more robust and resilient networked structures.

- **Fairness in Resource Distribution**:
  - Ensuring equitable computational power allocation in AI-driven decisions.
  - Addressing fairness in fields such as public infrastructure, healthcare, and finance.

- **Improving Adaptability in Dynamic Environments**:
  - Enabling flexible and responsive systems in traffic management, cloud computing, and financial markets.
  - Adapting resource distribution to evolving conditions for continuous optimization.

- **Maximizing Utility in Real-World Applications**:
  - Streamlining manufacturing, energy distribution, and supply chain management.
  - Minimizing waste while improving efficiency and system performance.

3. Adaptive Reweighting Mechanisms in Synchronization of Coupled Oscillators

- **Enhancing Synchronization in Weighted Networks**:
  - Investigating adaptive reweighting for network structures in dynamic systems.
  - Using synchrony alignment functions to rewire Kuramoto networks more effectively.

- **Mathematical Analysis of Network Adaptation**:
  - Conducting perturbation analyses to quantify the impact of varying edge weights.

  - Employing eigenvalue spectrum analysis to determine beneficial network modifications.

- **Rewiring and Reweighting Strategies**:
  - Proposing strategies that optimize phase synchrony in Kuramoto networks.

- **Human Learning and Network Modularity**:
  - Examining how modular network architectures affect learning and cognitive adaptability.
  - Studying functional connectivity changes in the brain during learning stages.

- **Temporal Dynamics of Learning and Flexibility**:
  - Assessing how network flexibility influences skill acquisition and automatic task execution.

- **Statistical Framework for Adaptive Networks**:
  - Building a generalizable statistical model to detect modular shifts in evolving networks.
  - Applying this framework to diverse domains where dynamic reconfiguration is crucial.

4. Dynamic Topological Data Analysis for Discriminating Transient Brain States in Neural Imaging

- **Distinguishing Transient Brain States**:
  - Creating methods to identify and classify evolving neural states.

- **Understanding Dynamic Collective Behavior**:
  - Uncovering functional variations through feature representations of brain regions.
  - Tracking temporal evolution in neural activity.

- **Applying Topological Data Analysis (TDA) to Neural Data**:
  - Developing TDA frameworks for high-dimensional neural imaging data.
  - Ensuring topological consistency across multiple time scales.

- **A Dynamic TDA-Based Monitoring Model**:
  - Real-time assessment of changes in brain network configurations.

  - Detecting state transitions and leveraging them for clinical insights.

- **Evaluating the Impact of Neural Dynamics**:
  - Studying cognitive and pathological state shifts through network analysis.
  - Simulating and interpreting potential brain states.

- **Guiding Cognitive and Medical Interventions**:
  - Providing early detection and intervention strategies through refined neural activity monitoring.

Through these initiatives, I seek to advance frameworks for adaptive decision-making under uncertainty, synchronization in dynamic systems, and neural state modeling. By integrating adversarial learning, network optimization, and TDA, my research aims to enhance both the theoretical underpinnings and real-world efficacy of mathematical modeling, cognitive modeling, and machine learning.

Conclusion

My work integrates mathematics with innovative computational strategies to tackle complex real-world problems. By combining insights from game theory, machine learning, network science, and topological data analysis, I strive to enhance decision-making, synchronization, and resource allocation across diverse applications. In the future, I remain committed to merging theoretical depth with practical impact, contributing to continued breakthroughs in AI, complex systems, and beyond.