Welcome!

AI for Algorithmic Reasoning and Optimization

About me

Grew up in Lincoln, Vermont

BA: Columbia
Math

PhD: Carnegie Mellon
Computer Science

Faculty: Stanford
Research:

- *Machine learning*
- *Algorithm design and*
- *Interface between Econ and CS*

Outline for today

1. **High-level overview**
2. Course outline
3. Course format
4. Policies
5. Project

AI for Algorithmic Reasoning & Opt

Core idea

- Models that **choose**, **design**, or **execute** algorithms
- Bridges LLMs, GNNs, optimization, and theory

Core capabilities (examples)

- Translate natural language into mathematical formulations
- Learn heuristics, policies, and solver configurations
- Simulate algorithmic primitives (search, DP, ...)
- Co-optimize models and solvers for performance gains

AI for Algorithmic Reasoning & Opt

In this class, we'll cover…

Evaluation principles

- Evaluate optimality, feasibility, generalization, efficiency

Applications and limits

- Power real-world systems: energy, logistics, markets, planning
- Recognize limits: NP-hardness, shifts, safety, …

Why now?

Advances in models

- Transformers enable in-context algorithm selection
- GNNs approximate local algorithms with growing theory
- Diffusion models generate structured, combinatorial solutions

Infrastructure

- Benchmarks and datasets across routing, scheduling, …
- Hardware and libraries support large-scale experimentation

Why now?

Applications

Power systems, logistics, etc. need learned decision systems

Foundations

Guarantees with predictions connect ML and classical theory

Community momentum

Seminars, workshops, tutorials, …

Key archetypes to organize the field

Select
Choose algorithms, heuristics, or configurations per instance

Simulate
Learn algorithmic primitives (e.g., BFS, DP, local search)

Co-optimize
Couple models and solvers in hybrid methods

Design
Discover new algorithms and heuristics

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Course map

Foundations (9/23 – 10/2)

Core ideas: GNNs, discrete optimization, approximation algorithms

Transformers & LLMs (10/7 – 10/16)

Graph Neural Networks (10/21 – 10/30)

Mathematical Optimization (11/6 – 11/13)

Theoretical Guarantees (11/18 – 11/20)

Alg. reasoning with transformers & LLMs

Goal: uncover algorithmic behaviors inside large seq. models

Core questions:

- What algorithms emerge from in-context learning?
- How do transformers select among candidate algorithms?
- Can LLMs design new heuristics (beyond selection)?

Algorithmic reasoning with GNNs

Goal: analyze how GNNs generate solutions to graph problems

Core questions:

- How powerful can GNNs be as approximation algorithms?
- Do GNNs benefit from learning related problems together?
- Can diffusion models be used to solve hard graph problems?

Mathematical optimization

Goal: connect ML/LLMs with optimization modeling & solving

Core questions:

- How can LLMs make optimization modeling more accessible?
- Can learning-guided search improve solver performance?
- What does it mean to make discrete opt. differentiable?

Theoretical guarantees

Goal: study when ML-guided optimization is provably reliable

Core questions:

- What can gradient methods guarantee for solution samplers?
- When can learned guidance be both useful and robust?

Course map

Foundations (9/23 – 10/2)

Core ideas: GNNs, discrete optimization, approximation algorithms

Transformers & LLMs (10/7 – 10/16)

In-context learning, algorithm selection, auto-design

Graph Neural Networks (10/21 – 10/30)

Approximation algorithms, dual reasoning, graph diffusion solvers

Mathematical Optimization (11/6 – 11/13)

LLMs for modeling, ML-guided search, differentiable discrete opt.

Theoretical Guarantees (11/18 – 11/20)

Policy-gradient landscapes, approximation with predictions

Big questions across the course

How do we **represent** algorithms in ML models?

How should we **evaluate** learned algorithms?

What are the **limits** – and **guarantees** – we can prove?

Where do these ideas matter in **practice**?

Something for everyone!

If you like **theory**:

- Provable guarantees for ML-guided algorithms
- Explore limits of LLMs, GNNs, etc. under NP-hardness

If you like **machine learning**:

- Study how transformers, GNNs, etc. reason algorithmically
- See how ML extends beyond prediction into problem-solving

Something for everyone!

If you like **optimization**:

- LLM-based modeling, ML-guided search, differentiable opt.
- Understand when ML improves—or fails to improve—solvers

If you like **applications**:

- Apply ideas to energy, logistics, finance, and markets
- Gain a toolkit for structuring real-world decision problems

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Two types of class sessions

Foundations lectures

Discussions

Foundations lectures

Cover the core background you'll need for the discussions

Topics include:

- Basics of graph neural networks
- Mathematical optimization
- Approximation algorithms
- Diffusion models

Format: Whiteboard

Research shows students retain concepts better this way

Discussions: the heart of the course

Most meetings will be student-led discussions

Each discussion covers one well-received paper from ’23-’25

Some days you’ll be a presenter, some days a non-presenter

The goal: spark conversations; analyze and build on ideas

Format of a discussion

Presenters:
- One of three roles (Archaeologist, Researcher, Reviewer)
- ~7 minutes presenting highlights + 3 minutes Q&A

Non-presenters:
- Post one discussion question on Ed by 1pm that day
- Join the class conversation

Professor:
- Closes each class with a 20-minute preview of the next paper
- Helps clarify what to focus on when reading

Archeologist

Situate the paper in context

Find one **older paper** it cites and explain the connection

Find one **newer paper** that cites it and explain the extension

Show how both relate to the paper's main idea

Researcher

Propose a follow-up project inspired by the paper

Ground it in the paper’s ideas, results, data, or code

NeurIPS reviewer

Critique the paper as if you're writing a review

Provide ≥3 strengths and ≥3 weaknesses

Address: quality, clarity, significance, originality

Non-presenter Ed discussion question

Characteristics of a good question:

- Specific: anchored in the paper's setup
- Forward-looking: invites thinking beyond what's tested
- Open-ended: there's no "right" answer, good for conversation
- Accessible: everyone in class can weigh in

Why this format?

Build research skills

- Learn to read papers quickly but deeply
- Practice asking sharp, thought-provoking questions
- From course evaluations: *"I'm a junior who had never done research before, but after this class, I feel equipped to do so."*

Shape your own projects

- See how to frame problems and methods
- Spot open directions for your final project

Why this format?

Join the research community

- Discussions mirror what happens at conferences

Make the class fun

- Conversations are more memorable than lectures
- You'll learn from each other, not just from me

Why this format?

- Format developed by Alec Jacobson & Colin Raffel (U of T)
- Great feedback here at Stanford!
  - *“Very helpful in developing my ability to read and digest research papers, in addition to engaging with them in an intellectually meaningful way.”*
  - *“The course format [was] a great way to interact with the various papers we read.”*
  - *“The seminar format led to some really cool conversations about potential extensions of the work, applications to other areas, etc. I wish more classes were structured like this.”*

Role logistics

Everyone will rotate through all three roles:

- Archaeologist
- Researcher
- Reviewer

Expect to be in each role once or twice during the quarter

- The exact count will depend on final enrollment

If the final enrollment is large, some roles may be done in teams

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Attendance: Lectures

Attendance is optional but recommended

These are the “Foundations” sessions on the schedule

Attendance: Discussions

Attendance is required

We know life happens (e.g., illness), so here's the policy:

- If scheduled as a Presenter:
  - You may miss one session
  - Must submit a video of your presentation within one week
- If scheduled as a Non-presenter:
  - You may miss up to two sessions
  - Still required to post your question on Ed

Grading breakdown

60 points: Discussion

- E.g., if 6× Presenter and 6× Non-presenter:
  - Each presentation = 8 points → total 48 points
  - Each non-presenter assignment = 2 points → total 12 points
- Subject to change depending on final enrollment

40 points: Project

Pass/fail option: Only discussion, no project

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Project overview

- Write a mini-paper (empirical, theoretical, or both)
- Option to work in groups (max 3 students) or solo
  - If in group: include specific contributions paragraph
- Groups expected to produce more work than solo projects
- Paper length: 3 + n pages (n = number of authors)
  - Excluding references & contributions
- Projects should show novelty
  - New application, method, or perspective

Milestones/deadlines

- 10/10: Topic interests spreadsheet
  - Fill in topics you're excited about
  - If you want a project partner, reach out to like-minded students
- 10/31: Progress report
  - 1-2 pages describing project + partial results
- 12/4: Final presentation
  - Present your final project in class
- 12/12: Final writeup due

Grading breakdown

Project matching spreadsheet – 3 points

Progress report – 7 points

Writing – 10 points (readability, completeness, context)

Novelty – 10 points (new idea, method, or perspective)

Final presentation – 10 points (clarity, insight into what you did)

Course Assistant

- TBA!

- They will have 5+ hours a week of bookable office hours
    - Take advantage of this for the course project!
    - Every year, at least one project turns into a NeurIPS/ICML paper
    - Meet with them (and me!) often to push project

Looking forward to a great quarter!