

Research Statement

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My research lies at the intersection of machine learning and formal methods, where I develop precise, mathematically grounded tools to analyze and improve the behavior of modern learning systems. As machine learning models grow in complexity and are increasingly deployed in high-stakes settings, there is a pressing need for principled approaches to reason about their learning dynamics, inference behavior, and trustworthiness. To this end, I draw on formal methods – such as logic, formal languages, and satisfiability solving – to examine how key properties of learning systems persist despite their stochasticity and scale. My goal is to build a verifiable and robust foundation of machine learning systems that are not only capable, but also trustworthy.

Summary of Research. My research is organized around two central themes: advancing a **foundational understanding of language models** and developing **trustworthy machine learning** for algorithmic decision-making. Large language models (LLMs) are complex generative machine learning (ML) systems with the potential for widespread application across domains. My work seeks to uncover the foundations of LLMs by studying their learning [1], memorization [2, 3], and inference behavior [4, 5]. In parallel, I explore issues of fairness [6–9] and interpretability [10–12] in ML systems, aiming to enhance their trustworthiness in high-stakes decision-making contexts. See Figure 1 for a high-level overview of how my research themes interconnect.

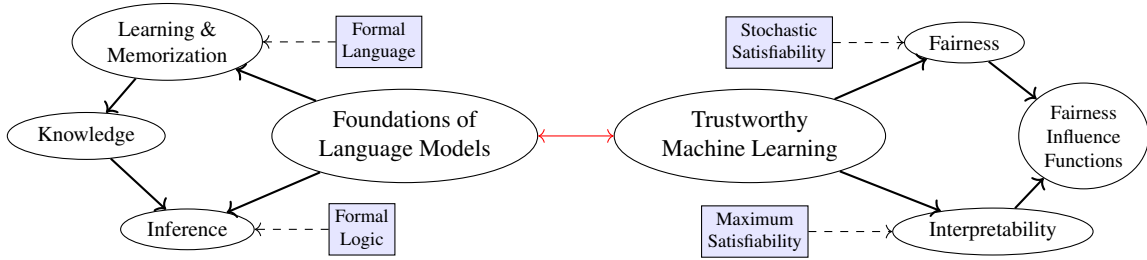


Figure 1: To better visualize the scope and interconnection between my research themes (ellipses) and methodological tools (blue boxes), Figure 1 presents a *keyword graph* that maps the relationships among core areas of inquiry and the formal methods I employ. Red arrows highlight my future research plans, focusing on the intersection of these themes and expanding beyond.

Beyond my core research themes, I have explored several other areas in computer science. This includes de-centralized machine learning, such as federated learning [13] and split learning [14]; graph-theoretic problems, including social-spatial group queries [15, 16] and core decomposition in hypergraphs [17]; and group testing [18].

Summary of Achievements. I have engaged in collaborative and interdisciplinary research at multiple academic institutions and industry, across three continents North America, Europe, and Asia. I conducted a research visit to INRIA, France, Goldman Sachs, India, and Max Planck Institute For Software Systems, Germany. My research is published at premier conferences on machine learning (ICLR, AAAI x 4, ECAI x 2, FAccT, AIES, WSDM, CAI) and databases (VLDB x 2), as well as journals in machine learning (JAIR) and databases (TSAS). I have presented a tutorial on *Auditing Bias of Machine Learning Algorithms: Tools and Overview* in IJCAI 2023. I was awarded NUS Research Scholarship, Singapore and Moblilex Scholarship at Université de Lille, France.

1 Research Theme 1: Foundational Understanding of Language Models

The first core theme of my research investigates foundational questions surrounding how large language models learn, memorize, and infer or generate. This theme is driven by the need for rigorous benchmarks and conceptual clarity around learning and inference in these complex systems.

1.1 Language Learning: Fine-tuning and In-context Learning

LLMs adapt to new domains via two learning modes: fine-tuning, where model weights are updated (closed-book learning), and in-context learning, where the LLM learns from examples in the prompt without altering model parameters (open-book learning).

Discriminative Test for Language Proficiency. What does it mean for an LLM to achieve language proficiency? Answering this is key to comparing language proficiency across models, languages, and learning modes. Rather than relying on absolute generative performance – which is non-comparable and impacted by model internals – we propose a discriminative test for language proficiency as the ability to generate the target language with higher probability than nearby languages.

Fine-tuning vs. in-context learning. In controlled formal language learning experiments [1], where syntactic pattern recognition abilities are required, we show that fine-tuning is more language proficient than in-context learning on in-distribution languages, while both perform similarly on out-of-distribution languages. This sheds light on the capabilities and limitations of LLM’s learning modes.

1.2 Rethinking Memorization Measures and their Implications

Memorization in LLMs is often viewed negatively due to privacy and copyright concerns and perceived as undesirable for learning. To critically assess this, we revisit existing privacy-focused memorization measures, such as recollection-based, and counterfactual memorization, and a newly proposed *contextual memorization* [2] – rooted in learning theory. Unlike recollection-based measures, contextual memorization finds a string-specific optimal contextual recollection threshold, where memorization is disentangled from contextual learning. Theoretically, contextual memorization is stricter than counterfactual memorization.

Disagreement when Operationalized. Our analysis reveals that these measures often disagree on the memorization order of training strings. Notably, improved optimal learning increases recollection-based memorization while reducing contextual and counterfactual memorization. Essentially, memorization – defined at individual training strings – is unavoidable for optimal learning – a global phenomenon.

Rethinking Memorization Risks. We also find that many strings previously flagged as memorized according to recollection do not contain sensitive information or satisfy contextual memorization criteria [3], suggesting that current threats of memorization are exaggerated. This work suggests a more nuanced understanding of contradictory implications of memorization measures.

1.3 Logical Consistency of LLMs

LLMs are applied to a growing range of tasks. What is a natural sanity check an end user can perform to verify the LLM’s understanding of the task? We propose a *logical consistency* test [4], which evaluates whether the LLM’s response remains consistent under logical transformations of the input prompt. Logical consistency is orthogonal to accuracy – an LLM may be incorrect, but its responses should still be consistent.

The need for logical consistency. Prior consistency criteria have primarily relied on paraphrasing-based input prompts. In contrast, logical consistency extends to logical transformations such as negation, conjunction, and disjunction, as well as rules like associativity, commutativity, and De Morgan’s laws – spanning propositional, first-order, and higher-order logic. Intuitively, negation consistency requires that a negated prompt yields a negated response, while conjunctive consistency implies that the response to a conjunctive prompt matches the conjunction of responses to its sub-prompts.

Logical consistency of LLMs in fact-checking. As a first step, we assess LLMs’ logical consistency in fact-checking tasks using knowledge graphs, where the model verifies input facts as true or false based on relevant extracted information. Our experiments show that logical consistency declines with fact complexity, while larger models tend to be more consistent, likely due to improved task understanding from scale. To enhance consistency, we propose an accuracy-driven approach using instruction fine-tuning and prompting.

1.4 Reliable Latent Knowledge Estimation in LLMs

LLMs acquire knowledge of the world through large-scale training corpora. However, due to the vulnerabilities of prompting – as illustrated by the consistency test above – directly querying an LLM is an unreliable method for estimating its knowledge. To address this, we propose a *zero-prompt, many-shot* approach for factual knowledge estimation [5]. Intuitively, if the LLM knows that “Germany’s capital is Berlin,” we present it with a pattern such as “France Paris; Italy Rome; Germany” and check whether it generates “Berlin” by inferring the underlying relation. This method avoids prompt hacking and side-channeling, relies on in-context learning, and remains agnostic to both model architecture and relation type.

2 Research Theme 2: Trustworthy Machine Learning

Complementing this foundational perspective, my second research theme focuses on developing trustworthy machine learning systems, particularly in contexts where fairness, interpretability, and societal impact are paramount. Here, I take a formal and computational approach to tackle pressing challenges in real-world ML deployments.

2.1 Formal Fairness Quantification and Explanation

Fairness in ML systems is a complex challenge, grounded in societal norms and beliefs. As a result, diverse fairness metrics have been developed to capture unfairness from various perspectives, along with corresponding mitigation algorithms. Central to these efforts is the need for *formal quantification of fairness* and the ability to *explain its underlying sources*.

2.1.1 Probabilistic Fairness Quantification

Towards quantifying *group-based fairness* of a binary ML classifier, the key objective is to compute the maximum (and minimum) probability of positive prediction across all sensitive groups, given the joint distribution of sensitive and non-sensitive features. The complexity of this problem grows exponentially with the number of sensitive attributes – such as race and gender – due to the combinatorial explosion of group partitions. Our focus is therefore on improving both the *scalability* and *accuracy* of fairness quantification.

We propose Justicia [6] by resorting to *stochastic Boolean satisfiability* (SSAT), a variant of Boolean satisfiability that models probabilistic decision-making with optimization. SSAT introduces logical choice variables (analogous to sensitive features) and random chance variables (analogous to non-sensitive features) to reason about the probability of a formula being satisfied (analogous to positive prediction). This modeling applies to tree-based and linear classifiers with white-box access to model parameters, and enables exact yet scalable fairness quantification compared to existing SMT and sampling methods – with scalability attributed to decades of advances in Boolean satisfiability solving.

2.1.2 Tractable Fairness Quantification

While SSAT has exponential worst-case complexity, can we achieve tractable fairness quantification for specific model classes such as linear classifiers? We show that probabilistic fairness quantification for linear classifiers admits *pseudo-polynomial* complexity by framing the problem as a novel *stochastic subset sum problem* (S3P) [7], inspired by SSAT. Tractability arises in two ways: identifying sensitive groups that always (and never) receive positive predictions is straightforward from the classifier’s feature coefficients, and S3P over non-sensitive features admits an efficient dynamic programming solution.

Encoding feature correlation. Both SSAT and S3P assume independence among random variables, limiting their ability to capture feature correlations. To address this, we model the input probability distribution using a Bayesian network and adapt SSAT and S3P accordingly. This enables efficient encoding of correlations and results in more accurate fairness quantification.

2.1.3 Universal Quantification for Group Fairness, Individual Fairness, and Robustness

Is it possible to quantify various distributional properties of a black-box model – without reconstruction – using a universal representation? In *active Fourier auditing* (AFA), we propose a Fourier-based quantifier for group fairness, individual fairness, and robustness [8]. The core idea is to approximate the model with a surrogate expressed in an orthonormal Fourier basis over input features, allowing these properties to be naturally formulated in terms of Fourier coefficients. We show that a PAC (probably approximately correct) estimate of each property can be obtained using only the significant coefficients, while also bounding the worst-case sample complexity.

2.1.4 Explaining Fairness: Identifying Sources of Unfairness

What if we could not only quantify unfairness but also explain its sources – analogous to feature attribution methods? Such explanations could help prevent unfairness [9]. To this end, we introduce *fairness influence functions* (FIFs) to measure the contribution of individual features and their intersections to overall unfairness. Inspired by global sensitivity analysis – which decomposes a function’s variance into contributions from input variables – we formalize FIFs for linear group fairness metrics. Like AFA, FIFs are model-agnostic and apply to any model expressible via orthonormal Fourier expansion. Their effectiveness is demonstrated by strong alignment with fairness interventions and fine-grained explanations of intersectional unfairness, absent in local explainability methods such as SHAP.

2.2 Interpretable Rule-based Classification

Complex, opaque models are not always necessary – indeed, in high-stakes settings like medical decision-making, interpretable and small models are often preferred. Rule-based classifiers, including decision trees, decision lists, and decision sets, form a prominent class of interpretable models. However, two key challenges persist: (1) the scalability of learning and (2) the limited expressiveness of the resulting rules.

2.2.1 Scalability via Incremental Learning

We adopt *conjunctive normal form* (CNF) as the hypothesis class for rule-based classifiers, as it underlies the structure of most rule-based models. The learning objective is to find smaller rules – enhancing interpretability – while preserving accuracy. We formulate optimal rule learning as a *maximum satisfiability* (MaxSAT) problem, where soft clauses encode learning objectives and hard clauses enforce constraints. However, the complexity of solving MaxSAT increases with the dataset’s dimensionality and the size of the classifier.

We propose an incremental MaxSAT-based learning framework, IMLI [10, 11], designed for scalable rule-based classification. IMLI combines mini-batch learning with iterative rule learning: it constructs a CNF classifier by progressively covering the training data, solving a sequence of smaller MaxSAT problems on mini-batches in each iteration by incrementally updating the learned rules. Empirically, IMLI achieves competitive accuracy and interpretability while scaling to datasets of million samples.

2.2.2 Expressiveness via Logical Relaxation

While rule-based classifiers offer interpretability, they often lack expressiveness. To address this, we introduce *relaxed-CNF* rules, which include tunable expressiveness parameters controlling how many literals per clause and how many clauses per formula must be satisfied to predict a positive class [12]. This combinatorial structure yields exponential succinctness over standard CNF and is commonly used in medical checklists (e.g., CHADS₂ score). To learn relaxed-CNF rules efficiently, we extend the incremental framework of IMLI by replacing the MaxSAT encoding with a *mixed integer linear program* (MILP). Empirically, relaxed-CNF rules maintain similar accuracy while being smaller in size than other rule-based classifiers.

3 Future Directions and Vision

My research at the intersection of machine learning and formal methods has allowed me to approach core computational problems from multiple perspectives, which I see as essential to shaping my future work. As machine learning continues to evolve, I aim to leverage ideas from automated reasoning and formal methods to both analyze and improve learning systems. *My long-term vision is to build a foundational understanding of learning systems that enhances their capabilities and trustworthiness, while enabling formal certification of their behavior.* Below, I outline two broader research directions that will guide this vision.

Controlled Benchmarking of Machine Learning. Benchmarking plays a central role in the development of machine learning, and formal methods hold significant promise for its future. This includes the design of synthetic, controlled datasets and environments; formal modeling and evaluation of ML behavior; and formal quantification of how well ML systems align with human values. In modeling, formal methods naturally separate the concerns of specification and solution: we can model safety-critical properties of ML systems while leveraging scalable solvers developed in the formal methods community to verify them. Conversely, the complexities and ambiguities of modern ML systems offer compelling challenges that can inform and expand the scope of formal methods. In the coming years, I plan to advance our understanding of learning systems by systematically integrating these two perspectives.

Generative AI for Improved Problem-Solving. The widespread adoption of generative AI (artificial intelligence) has transformed how humans interact with machines in problem-solving tasks. LLMs and related systems can act as effective collaborators – despite their imperfections, they can assist in generating useful hypotheses, supporting exploratory thinking, and improving creative workflows. My research aims to apply generative AI for enhanced hypothesis construction, idea generation, and decision-making, aligned with emerging paradigms in agentic AI and human-computer interaction. Alongside these goals, I seek to investigate what forms of formal guarantees and reliability can be achieved in the context of AI-human collaborative systems.

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