Integrating Logic and Causal Reasoning for Learning and Control in Autonomous Systems

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Abstract
Artificial intelligence, powered by data-driven methods, has surpassed human-level performance in many tasks. Yet deploying AI in autonomous systems remains fundamentally challenging due to limited interpretability, high data demands, and insufficient logical and causal reasoning in decision-making. To address these challenges, this talk presents interpretable and data-efficient learning approaches that integrate theories and techniques from machine learning, formal methods, and control theory. Unlike traditional learning approaches, these methods enable agents to reason over their learning processes, coordinate effectively with other agents, efficiently enhance operational capabilities to complete complex tasks in the presence of competitors or adversaries, and swiftly adapt to novel tasks and environments.

The first part of the talk focuses on learning high-level logical and causal knowledge from data and its application to physical systems. I present state-of-the-art methods for learning temporal logic (TL) formulas and TL-based causal diagrams from data. The second part addresses improving the sample efficiency of reinforcement learning (RL) using high-level knowledge. I introduce a neuro-symbolic RL framework based on offline training followed by online fine-tuning, which enables an agent to reason about its exploration process and distill high-level knowledge from both offline datasets and online interactions to guide future exploration. I also present approaches that leverage large language models and causal reasoning to further accelerate RL. The final part of the talk focuses on learning and control in multi-agent systems operating in cooperative, non-cooperative, and incomplete-information stochastic games, where logical and causal knowledge is discovered in a distributed manner.

Bio
Zhe Xu is an Assistant Professor in the School for Engineering of Matter, Transport, and Energy at Arizona State University. Prior to joining ASU, he was a postdoctoral researcher at the Oden Institute for Computational Engineering and Sciences at The University of Texas at Austin. He received his Ph.D. in Electrical Engineering from Rensselaer Polytechnic Institute in 2018. Dr. Xu is a recipient of the NSF CAREER Award, the Howard Kaufman ’62 Memorial Fellowship, and the ASU Fulton Schools of Engineering Teaching Recognition Awards (2023–2025). His research interests include formal methods, autonomous systems, control systems, and reinforcement learning. He has developed learning, control, and verification methods with applications in robotics, power systems, smart buildings, and biological systems.

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