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Q-Learning in Reinforcement Learning: Principles, Applications, and Emerging Challenges

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Abstract: *Reinforcement Learning (RL) is a prominent paradigm in artificial intelligence where agents learn optimal behaviors through interactions with an environment, guided by reward feedback. Among various RL algorithms, Q-learning stands out as a foundational model-free technique that enables agents to learn value functions without prior knowledge of environment dynamics. This paper presents a comprehensive study of Q-learning, starting with its theoretical basis and mathematical formulation. We examine the key features that make Q-learning effective, including its off-policy nature, convergence guarantees, and adaptability to different domains. Applications of Q-learning are explored in fields such as autonomous systems, robotics, gaming, healthcare, and finance, highlighting its practical significance. The paper also discusses major challenges in Q-learning, including issues with sample inefficiency, exploration-exploitation balance, and scalability in high-dimensional environments. Recent innovations like Deep Q-Networks (DQNs), Double Q-learning, and prioritized experience replay are reviewed as solutions to these limitations. Finally, we propose future directions for research aimed at improving generalization, stability, and real-time applicability of Q-learning algorithms..*

Keywords: Reinforcement Learning

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