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Evolutionary Game Theory: A General Review

Evrimsel Oyun Teorisi: Genel Bir İnceleme

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ABSTRACT

This article surveys the Evolutionary Game Theory (now EGT), encompassing its historical underpinnings, recent advancements, and future potential. Originating in the 1970s through the pioneering work of John Maynard Smith and George R. Price, EGT leverages game-theoretic concepts to elucidate the evolution of strategies within various populations across biological, economic, and social domains. Notably, recent progress has seen the integration of advanced large language models (LLMs) such as GPT-3.5 and GPT-4 into agent-based simulations, thereby enriching the authenticity and intricacy of strategic interactions. Additionally, the study addresses the complexities associated with modeling diverse behaviors and bridging the insights derived from LLMs to practical applications in fields like biology, healthcare, education, and social sciences. Moreover, it highlights the importance of interdisciplinary collaboration and innovative methodologies in tackling the complex challenges associated with EGT. The article also reflects on potential directions for future research, stressing the integration of EGT with practical applications and the need for comprehensive models that capture the intricacies of evolutionary dynamics in adaptive systems.

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ÖZ

Bu makale, Evrimsel Oyun Teorisinin (EOT) tarihsel temellerini, teoride yaşanan son gelişmeleri ve evrimsel oyun teorisinin gelecekteki potansiyel evrimini incelemektedir. 1970'lerde John Maynard Smith ve George R. Price'ın öncü çalışmalarıyla ortaya çıkan EOT, biyolojik, ekonomik ve sosyal alanlardaki çeşitli stratejilerin evrimini araştırmak için oyun teorisi kavramlarından yararlanmakta ve dönemler arası etkileşimi sağlamaktadır. EOT özellikle son zamanlarda GPT-3.5 ve GPT-4 gibi geniş dil modellerinin ajan bazlı simülasyonlara entegre edilmesiyle daha da zengin bir literatüre kavuşmuştur. Bu çalışma ayrıca, farklı davranışların modellenmesi ve geniş dil modellerinden elde edilen içgörülerin biyoloji, sağlık, eğitim ve sosyal bilimler gibi alanlardaki pratik uygulamalarla birleştirilmesiyle ilgili karmaşıklıkları ele almaktadır. Ayrıca, evrimsel oyun teorisindeki çok yönlü zorlukların ele alınmasında disiplinler arası işbirliğinin ve yenilikçi metodolojilerin öneminin altını çizmektedir. Son olarak

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çalışmamız, EOT'nin gelecekteki potansiyel evrimini inceleyerek, EOT'nin adaptif sistemlerdeki evrimsel dinamiklerin karmaşıklığını kapsayan kapsamlı modeller ile zenginleştirilmesi gerektiğini vurgulamaktadır.

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1. INTRODUCTION

Evolutionary Game Theory (EGT) is a multifaceted framework that merges the foundational principles of classical game theory with the tenets of evolutionary biology. Its primary purpose is to understand and predict the strategic interactions among individuals in diverse ecological and social settings. Originating from the groundbreaking contributions of John Maynard Smith on Evolutionarily Stable Strategies (ESS) in the 1970s, EGT has undergone substantial advancements, delving into biological phenomena and extending its applications to economic and social behaviors. It has established itself as a useful analytical tool used by scholars across a wide range of fields, including psychology, sociology, anthropology, and economics. This interdisciplinary approach has proven invaluable in elucidating complex population behaviors and dynamics, contributing to a deeper understanding of various societal and ecological phenomena.

The primary goal of this article is to provide an in-depth examination of Evolutionary Game Theory (EGT), highlighting its historical origins, recent advancements—including the integration of large language models such as GPT-3.5 and GPT-4 into simulations—and its potential future applications. It emphasizes the interdisciplinary challenges inherent in modeling complex behaviors and applying EGT insights to practical domains such as biology, healthcare, education, and the social sciences. Additionally, the article emphasizes the necessity for innovative methodologies and continuous research to create robust models for real-world adaptive systems..

For this purpose, the paper will begin with a literature review of evolutionary game theory, exploring its foundational principles, emergence, and development over time. The second section will assess current advancements, particularly the role of artificial intelligence in enhancing evolutionary game theory, along with its recent applications in areas such as cancer treatment, the reconstruction of educational systems following the pandemic, network theory and cooperative dynamics in non-biological systems. Subsequently, the limitations of the theory and the challenges it faces will be addressed. Finally, the paper will explore the future directions of evolutionary game theory.

The foundational principles of EGT have been instrumental in modeling the evolution and stability of strategies within populations. Concepts such as Evolutionarily Stable Strategy (ESS) and replicator dynamics have provided deep insights into behaviors like cooperation, altruism, and competition. Recent advancements in EGT have significantly expanded its applicability, including refining the ESS concept and investigating the impact of network models, spatial and temporal effects, and strategy update rules on evolutionary dynamics.

The field has seen significant contributions from influential figures such as Robert Axelrod and William D. Hamilton (1981), whose work has had a substantial impact and shaped the field. Hamilton's pioneering research on kin selection and Axelrod's influential studies on the evolution of cooperation through iterative prisoner's dilemma games have been particularly noteworthy. These contributions have provided deep insights into the mechanisms governing cooperation and altruism within biological systems, continuing to significantly influence our understanding of social behavior dynamics and evolutionary outcomes.

During the 1990s and early 2000s, EGT underwent substantial growth and broadened its scope from its biological roots to encompass economic and social dimensions. Esteemed academics such as Jörgen Weibull and Fernando Vega-Redondo (Standford Encyclopedia of Philosophy, 2021) were instrumental in this broadening, undertaking extensive research that applied EGT to economic contexts. Their work delved into the development of strategies in competitive and cooperative environments among individuals.

During this time, evolutionary game theory (EGT) garnered significant attention and interest from various academic disciplines, particularly in the fields of psychology, sociology, and anthropology due to its interdisciplinary approach. This period marked a significant integration of principles from behavioral game theory into EGT, leading to a more comprehensive understanding of human behavior. Notably, eminent researchers such as Colin Camerer and Ernst Fehr (2002) played pivotal roles in conducting rigorous experiments to study human altruism and social preferences, thus making substantive contributions to the advancement of the field.

Philosophical exploration has significantly influenced the foundational principles of game theory. LaCasse and Ross (1994) have made noteworthy contributions by clarifying the philosophical foundations of these principles. Additionally, Ross and LaCasse (1995) have explained the intricate connections between games and the fundamental assumptions of microeconomics and macroeconomics. These works have provided valuable insights into the philosophical foundations of game theory and its connections to larger economic theories.

Evolutionary game theory (EGT) has proven its capacity to analyze complex behaviors across a variety of domains, illustrating its practical applications in understanding human social interactions and the formation of social structures. For example, a study conducted by Henrich et al. (2015) involved economic experiments in small-scale communities and provided empirical evidence that supports the principles of evolutionary game theory. This highlights the theory's relevance across different cultural contexts and its significant contributions to theoretical advancements in the field.

In addition to these important studies, there are other studies that contribute to the evolutionary game theory literature. Straub (1995) conducted an important study comparing risk-dominant and return-dominant strategies. Accordingly, the simultaneous existence of return-dominant and risk-dominant balances in a game may cause coordination problems.

Young (1998) has shown that under individual best response dynamics with monotonic error terms, stochastically stable states converge to the Kalai-Smorodinsky (Kalai & Smorodinsky, 1975) bargaining solution. Young discusses a conventional process in which players' expectations evolve through repeated interactions in a widely populated environment. Agents apply the best response rule to the best of their knowledge and are subject to inertia and some random error. In the long run, this adaptive learning process selects efficient and equitable contracts.

Naidu et al. (2010) examined equilibrium choices in stochastic evolutionary bargaining games. Accordingly, in coordination games, the Nash bargaining solution is the stochastic steady state chosen by the non-random conditions specific to the game. Roca et al. (2010) examined evolutionary games in real social networks, focusing on coordination games. In the study, it was determined that the coordination of the same type of behavior was a failure in populations where the parameters were very diverse. It was concluded that the result was due to topological problems.

Newton (2012) discussed the idea of cooperative behavior of groups of people acting together for their mutual benefit and explained it with evolutionary game theory. The study defined an equilibrium selection criterion called coalitional stochastic stability. This criterion uses the possibility of deviation from conventions by groups of players as an equilibrium selection tool in evolutionary social learning models. It has a different result than Young (1998)'s research in terms of using the extended model with coalition dynamics and showing that stochastically stable situations converge to the Nash solution.

Using evolutionary game theory tools, Gou and Deng (2021) examined evolutionary decision processes and stationary strategies in multiplayer systems. Gamers have been described as adapters, leaders, followers, and loners. Accordingly, the following results were obtained:

- Leader players are of great importance in increasing communication success.
- Positive feedback is important for followers. Blocking the exchange of information can be penalized to reduce the cost of diffusion of information affecting behavior, which can increase cooperation to facilitate evolutionary convergence toward the ideal state.
- Incentives resulting from the communication success and positive feedback of leading players also increase cooperation between loners and other types of players and reduce coordination failures.

Staugidl (2011) showed that risk dominant strategies can be stochastically stable equilibria. Based on the impactful research published in 2016 by Alger and Weibull, it was demonstrated that a specific moral choice category known as Homo-moralis is evolutionarily stable. This means that this particular moral preference class exhibits stability from an evolutionary standpoint. Conversely, moral preference classes other than homo-moralis were found to lack evolutionary stability.

Canbolat et al., (2016) highlighted if the players-agents are identical and the game is symmetric, the evolutionary strategic stable equilibrium should be a Nash equilibrium. Mielke and Steudle (2018) noted that uncertainty is a key reason for the failure of non-cooperative coordination games to coordinate a payoff dominant equilibrium. They suggested that one way to address this issue is by altering the yield structure to reduce uncertainty, or by considering subjective probabilities.

In a study conducted by Bilancini et al. in 2018, it was highlighted that cooperation can be established among individuals with diverse preferences and cultural backgrounds within a heterogeneous population divided into two distinct cultural groups throughout evolution. Fan and Hui (2020) discovered a significant reason for the evolution of strategies and behaviors: individuals from different groups can observe and learn from each other to determine the most appropriate strategy through trial and error.

In a study conducted by Dong et al. (2020), an evolutionary game model was developed to analyze stock prices. The model considers various factors such as potential revenue or loss, the probability of gain or loss, and the cost of corresponding behavior to understand the impact of investors' decisions on stock investment. The research revealed that reducing speculation, increasing access to information, and enhancing market information disclosure mechanisms can mitigate price synchronicity (volatility) in the stock market. Hence, the transparency and accessibility of information in markets are more important than the rational behavior of economic agents. This suggests that having access to accurate information is more crucial than individuals' behaviors in the market.

Shleifer's (2000) study suggested that random choice strategies might lead to higher profits than rational strategies. However, whether randomly selected investment strategies can maintain their stability over time is still unknown.

Similarly, Brock et al. (2005) conducted a study indicating that entirely rational behavior is not essential for a rational investment market. Their research showed that an evolutionary market system might become unstable if investors are overly sensitive to small return differences between strategies. These results suggest that Friedman and Fama's findings are valid only in certain situations. Nevertheless, Hens and Hoppe's (2005) research indicated that financial and insurance markets can maintain stability if a dominating strategy increases its market share over another.

Evstigneev et al. (2006) demonstrated the importance of evaluating stocks based on expected relative dividends to maintain an evolutionary stable stock market. The introduction of any other market can potentially lead to an invasion by a portfolio rule that can increase its market share at the expense of the incumbent. Introducing this portfolio rule can result in a shift in asset valuation over time.

Blume and Easley's study (2006) examined Pareto optimal consumption allocations in a stochastic general equilibrium model, focusing on the market selection hypothesis. They found that in complete markets, Pareto optimal equilibrium allocations are achieved. However, in incomplete markets, the long-term survival of the economy may depend on the payoff functions, and the market selection hypothesis may not be applicable. This suggests that it's uncertain whether the investment market will eventually be controlled by agents whose beliefs are most aligned with reality. Assuming investors with rational expectations have the most accurate expectations highlights that the dominance of rational investors in the market in the long term is not guaranteed. This study examines how returns are influenced by a specific state of nature, which is itself shaped by an evolutionary process. Furthermore, it models scenarios where this evolutionary process also plays a role in determining the wealth of investors.

EGT has also found applications in the healthcare sector, particularly in modeling the propagation of infectious diseases and evaluating the efficacy of interventions. One notable application involves the development of agent-based models that incorporate EGT principles to replicate the dynamics of the COVID-19 epidemic. These sophisticated models have proven crucial in assessing the impact of measures such as social distancing and other public health interventions on disease transmission (Bukkuri & Brown, 2021). These models play a pivotal role in supporting public health planning and response efforts by generating valuable predictions and conducting evaluations of diverse intervention strategies.

In education, EGT serves as a valuable tool for analyzing the complex dynamics between students and educational institutions, especially within the context of integrating artificial intelligence (AI). By employing EGT, researchers can delve into the interactive behaviors of schools and students, viewing them as active agents involved in strategic decision-making. This is often represented using payoff matrices that outline the costs and benefits associated with various courses of action. Through this approach, we gain insights into the impact of AI on teaching methodologies, allocation of resources, and overall academic performance (Newton, 2018). Although EGT proves to be a robust framework for studying AI integration in education, it also brings to light several challenges. One notable obstacle is educational institutions' potential lack of motivation to effectively supervise AI systems. Additionally, students may encounter difficulties in adapting to AI-generated content, necessitating additional efforts to bridge the gap between traditional educational methods and AI-driven approaches.

Finally, EGT has significantly contributed to the field of social sciences by creating models for human cooperation, competition, and social networks. EGT has played a crucial role in the establishment of societies such as the North American Association for Computational Social and Organizational Sciences (NAACSOS), which is dedicated to developing computational models for social networks and organizational behavior. These models help us understand the evolution of social structures and the mechanisms underlying human interactions within various organizational settings.

Studies related to the field, which has a vast and rich literature, are categorized according to subject headings (Table 1).

As discussed in this section, the evolutionary game theory literature is rich and comprehensive. The subsequent section will focus on recent advancements in this field, particularly in relation to the integration of artificial intelligence, as well as four contemporary application areas where evolutionary game theory is being effectively employed.

2. RECENT DEVELOPMENTS, ADVANTAGES AND CHALLENGES

The vast collection of literature on Evolutionary Game Theory offers valuable insights into a wide range of areas including biology, economics, and social sciences. The field, however, is undergoing significant advancements, accompanied by criticisms, challenges, and limitations. In this section, we will explore these emerging developments and the associated issues in greater depth.

2.1. The Effect of LLMs and AI

The escalating intricacy of Multi-Agent Systems (MASs), combined with the rise of Artificial Intelligence (AI) and Large Language Models (LLMs), has brought to light substantial gaps in our comprehension of the conduct and interfaces of diverse entities in dynamic environments. While traditional game theory approaches have been commonly employed in this domain, their effectiveness is impeded by the static and uniform nature of their models. A more dynamic and nuanced theoretical framework is essential because of the transformative impact of AI and LLMs on business and society. This framework transcends game theory by acknowledging and tackling the diverse

Table 1. Literature of evolutionary game theory

Field	Author(s)	Description
Kin Selection and Cooperation	Axelrod & Hamilton (1981)	Pioneered research on kin selection, offering insights into cooperative behavior.
Moral Preferences and Stability	Alger & Weibull (2016)	*Homo-moralis* is identified as an evolutionarily stable moral preference class, unlike other moral preference categories.
Coordination Challenges	Straub (1995), Staugidl (2011)	The coexistence of risk-dominant and return-dominant strategies can lead to coordination issues (Straub,1995). Risk-dominant strategies may act as stochastically stable equilibria (Staugidl, 2011).
Adaptive Learning and Bargainin	Young (1998), Newton (2012)	Adaptive learning processes with monotonic error terms lead to Kalai-Smorodinsky bargaining solutions (Young, 1998). Introduced coalitional stochastic stability, showing how groups deviate from conventions to reach Nash equilibria (Newton, 2012).
Cross-Cultural Learning	Henrich et al. (2015), Fan & Hui (2020)	Provided empirical evidence supporting EGT principles in small-scale cultural contexts (Henrich et al, 2015). Observational learning across groups enhances evolutionary convergence to optimal strategies (Fan & Hui, 2020).
Impact of Leaders and Communication	Gou & Deng (2021)	Leaders enhance communication success, and positive feedback among players fosters cooperation, reducing coordination failures (Gou & Deng, 2021).
Stock Market Dynamics	Dong et al. (2020), Shleifer (2000), Evstigneev et al. (2006)	Stock prices influenced by access to market information and reduced speculation (Dong et al, 2020). Random choice strategies may yield higher profits than rational strategies under certain conditions (Shleifer, 2000). Evolutionarily stable stock markets rely on expected relative dividends for valuation (Evstigneev et al at., 2006).
Market Stability and Risk	Hens & Hoppe (2005), Mielke & Steudle (2018)	Dominating strategies improve financial and insurance market stability (Hens & Hoppe, 2005). Reducing uncertainty in yield structures facilitates payoff-dominant equilibria (Mielke & Steudle, 2018).
Cultural Diversity in Economic Behavior	Bilancini et al. (2018)	Cooperation can emerge in heterogeneous populations with diverse cultural preferences (Bilancini et al., 2018).
Dynamic Bargaining	Naidu el al. (2010), Roca et al. (2010)	Stochastic equilibrium choices in coordination games converge to Nash solutions (Naidu et al., 2010). Coordination failures in populations with highly diverse parameters, due to topological issues (Roca et al., 2010).
Game Theoretical Application	Blume & Easley (2006)	Incomplete markets may disrupt Pareto optimal allocations, challenging the market selection hypothesis (Blume & Easley, 2006).
Healthcare, Disease Dynamics	Bukkuri & Brown (2021)	EGT-based models simulated COVID-19 dynamics, aiding in evaluating interventions like social distancing (Bukkuri & Brown, 2021).
Education, AL Integration	Newton (2018)	EGT models explored the strategic interaction between students and educational institutions in AI-driven environments, revealing challenges in supervision and adaptation (Newton, 2018).
Philosophical Foundations	LaCasse & Ross (1994) , Ross & LaCasse (1995)	Clarified philosophical principles underlying game theory (LaCasse & Ross, 1994). Linked game theory assumptions to microeconomic and macroeconomic principles (Ross & LaCasse, 1995).

Source: Prepared by author.

interactions (economic transactions, social relationships, information exchange) and the disparities in risk aversion, social preferences, and learning capabilities among entities.

The recent progress in evolutionary game theory has emphasized the significant role of large language models (LLMs) in improving agent-based modeling and simulation. Traditional agent-based models rely on simple rules or limited-intelligence neural models to imitate the behaviors of agents within a system. However, integrating LLMs, such as GPT-3.5 and GPT-4, into these models has brought about a new level of complexity and intelligence, making it possible to create more sophisticated and human-like agents (Gao et al., 2023).

Large language models (LLMs) have enhanced the simulation of complex systems in various domains, including cyber, physical, social, and hybrid environments. They have been used to simulate economic activities, social interactions, and market behaviors more accurately. Researchers can create more realistic simulation environments by using LLMs and developing agents capable of advanced strategic reasoning and adaptive behavior. Although LLMs generally display rationality to some extent, they often do not reach Nash equilibrium. Among the tested LLMs, GPT-4 has demonstrated superior strategic reasoning abilities and quicker convergence to Nash equilibrium compared to other models such as GPT-3.5.

In their 2023 study, Zarza and colleagues emphasized the significant potential of leveraging large language models (LLMs) to facilitate cooperation, enhance social welfare, and promote resilient strategies within multi-agent environments. The proposed Evolutionary Computation (EC) framework provides valuable insights into the intricate interplay between strategic decision making, adaptive learning, and guidance informed by LLMs in complex and ever-changing systems. This research addresses the challenges of modeling Multi-Agent Systems (MASs) and sets the stage for further exploration and advancement in this rapidly evolving field.

In their research, Suzuki and Arita (2024) seek to illustrate the capacity of large language models (LLMs) in advancing the study of human behavioral evolution through the application of evolutionary game theory. They propose an evolutionary model using LLMs loaded with high-level psychological and cognitive character descriptions to simulate human behavior choices in game-theoretical scenarios. The initial phase involves introducing an evolutionary model of personality traits associated with cooperative behavior, utilizing a comprehensive language model.

In this model, linguistic descriptions of personality traits related to cooperative behavior are treated as genes, and the deterministic strategies derived from the LLMs. The population evolves through selection based on the average payoff and mutation of genes by instructing the LLM to modify the parent gene towards cooperative or selfish traits slightly. Through experiments and analyses, they demonstrate that such a model can exhibit the evolution of cooperative behavior based on diverse and higher-order representations of personality traits. The researchers noted multiple occurrences of cooperative and selfish personality traits arising from variations in the manifestation of personality traits. The terms that surfaced in the modified genes mirrored the behavioral inclinations of the linked personalities in semantic terms, impacting individual behavior and evolutionary dynamics.

In their 2023 paper, You et al. emphasized the potential benefits of appropriately applying AI in education while highlighting the potential for harm through its misuse. The authors used EGT to explore AI's potential in the future of education. By studying the behavior of two agents, the school and the students, they aimed to identify strategies to enhance the effectiveness of the education model in the AI era. They developed a stable evolutionary strategy for the school and the students across various scenarios. In their study, the authors performed a detailed numerical analysis to investigate the influence of various essential factors on developing a stable strategy. The analysis findings indicated that it would benefit educational institutions to establish robust supervision mechanisms to effectively manage AI integration in education. Moreover, the results highlighted the importance of students proactively embracing and interacting with AI technology to maximize its potential benefits in the educational context.

Han et al. (2020) developed an AI model that simulated different hypothetical scenarios for AI races to determine which AI races should be prioritized for regulatory oversight. The team's model had to account for the complex choices involved when there was no predetermined path, so it integrated various concepts from biology and mathematics, such as EGT. Researchers conducted multiple simulations, tweaking the variables to observe the long-term outcomes. They used a model with virtual agents as competitors in simulated AI races, each with randomly assigned behaviors reflecting real-world situations. Some agents were cautious while others took more risks, leading to AI products that were inadequately tested or vulnerable to hacking and data leaks. The researchers found that the most crucial factor was the length of the AI race, which determined the time taken to produce a functional AI product.

Recent developments in evolutionary game theory have emphasized the important contribution of large language models (LLMs) in improving agent-based modeling and simulation, as demonstrated earlier.

2.2. Treatment of Cancer

A very recent application of EGT is the modeling of cancer treatment. For many years, the conventional approach to treating cancer involved administering the maximum tolerated dose of a medication to target a high number of cancer cells with minimal side effects.However, the cells that make up a tumor are diverse. Some of these cells develop mutations, or changes in their genetic material, by chance, making them resistant to a drug. These resistant cells can then grow and repopulate the tumor, leading to therapeutic resistance that renders the drug ineffective.

In such cases, physicians typically transition to an alternative medication that addresses a distinct characteristic of the cancer cells. This process continues until a treatment can effectively control the cancer or until no more drugs are available. If no more drugs are available, patients are then provided with hospice care to ensure their last days are as comfortable as possible.

To improve long-term patient outcomes, cancer researchers seek answers to two fundamental questions: What drives tumor growth, and how do tumors develop resistance? An ecological and evolutionary approach to studying cancer, which examines how the body's environment influences and is influenced by evolving cancer cells over time, offers valuable insights into these queries (Bukkuri, 2021).

Understanding the impact of selective pressures, external factors influencing an organism's survival. Evolutionary game theory provides valuable insights into the dynamics of interactions between cancer cells and their environment, helping researchers comprehend the effects of these selective pressures. Hence, EGT offers valuable insights for researchers and oncologists in forecasting cancer response to various treatments and potentially influencing the evolutionary path of cancer. This knowledge holds the potential to optimize patient outcomes.

Substantial strides have been taken in cancer treatment, yet there remains a substantial challenge in rendering all cancer types treatable conditions. One encouraging strategy for reaching this objective involves harnessing evolutionary mechanisms to consistently exert selective pressure on cancer cells.

Some important articles are also in this field. Orlando et al. (2016) discussed cancer treatment as a strategic game, where oncologists select a therapy and tumors adapt. They suggested that oncologists can gain an advantage by choosing treatment strategies that anticipate tumor adaptations. The study examined the potential benefits of exploiting evolutionary tradeoffs in tumor adaptations to therapy. The authors analyzed a mathematical model in which cancer cells faced tradeoffs in allocating resistance to two drugs. The tumor "chooses" its strategy through natural selection, while the oncologist selects her strategy by solving a control problem. The study found that when tumor cells perform best by investing resources to maximize their response to one drug, the optimal therapy is a consistent delivery of both drugs simultaneously. The study also emphasized that drug interactions can significantly alter these results. In conclusion, the authors stressed the importance of understanding both evolutionary tradeoffs and drug interactions in planning optimal chemotherapy schedules for individual patients.

Czako et al. (2017) provided a model aiming to reduce medical expenses during cancer treatment by creating personalized administration plans with the help of control engineerin. Kaznatcheev and colleagues (2017) introduced the double goods game to explore the dynamics of certain traits using evolutionary game theory. They used glycolytic acid production to represent a public good for all tumor cells, and vascular endothelial growth factor production for oxygen from vascularization as a club good benefiting non-glycolytic tumor cells. This resulted in three viable phenotypic strategies: glycolytic, angiogenic, and aerobic non-angiogenic. Authors have categorized the dynamics into three different types: (1) fully glycolytic, (2) fully angiogenic, and (3) polyclonal in all three cell types. The third type allows for dynamic heterogeneity even with linear goods, which was not possible in prior public good models that only considered glycolysis or growth factor production in isolation.

In 2018, West et al. constructed a mathematical model centered on the replicator dynamics of three interacting cell populations: cooperative (healthy), defecting (sensitive), and resistant (defecting) cells.This model mirrored prostate-specific antigen measurement data from three clinical trials for metastatic castration-resistant prostate cancer patients treated with different medications. The study found that continuous maximum tolerated dose schedules initially reduced the sensitive cell population, decreasing tumor burden. However, this allowed the resistant cells to thrive and regrow the tumor in a resistant form. The researchers used this evolutionary model to evaluate responses to conventional therapeutic strategies and design adaptive strategies, which were found to be robust to small timing changes and extended the simulated time to relapse from continuous therapy administration.

Stankova et al. (2019) studied cancer treatment as a game involving the physician's therapy and the cancer cells' resistance strategies. This game has two important differences: (1) Only the physician can make rational decisions. Cancer cells can only adapt to current conditions; they cannot predict or evolve adaptations for treatments that the physician has not yet applied. (2) It has a unique leader-follower (or "Stackelberg") dynamic; the oncologist takes the lead by making the first move, and the cancer cells then respond and adapt to the therapy. Current treatment protocols for metastatic cancer usually do not take advantage of these differences. Through the repetitive administration of the same drug(s) until disease progression, the physician employs a static approach while the cancer cells continuously evolve to develop effective adaptive responses. Additionally, by altering treatment only upon tumor progression, the physician effectively allows the cancer cells to dictate the course of treatment, leading to almost certain treatment failure. Without fundamental changes in strategy, conventional cancer therapy typically leads to "Nash solutions," where no individual change in treatment can enhance the outcome.

Bayer et al. (2021) utilized game theory tools to create a Markov chain model for cancer treatment. The model represents cancer therapy as a patient's Markov Decision

Problem, aiming to maximize the patient's discounted expected quality of life years. Patients can choose the number of treatment rounds based on the progression of the disease and their own preferences. The authors developed an analytical decision tool that allows patients to select their preferred treatment strategy. In another model, patients can also decide on the timing of treatment rounds. By delaying therapy, patients can postpone the side effects while forgoing the benefits for a period. The authors obtained an analytical tool that enables numerical approximations of the optimal delay times.

Wölf et al. (2022) described cancer as an evolutionary game, consisting of cells of different types undergoing frequency-dependent selection. In the article, it was provided an overview of previous studies that used evolutionary game theory to model cancer and improve its treatment. Some of these game-theoretic models suggest potential strategies to predict and guide cancer's eco-evolutionary dynamics towards more favorable states for the patient through evolutionary therapies. These therapies promise to improve patient survival and reduce drug toxicity, as evidenced by recent studies and clinical trials.

During the discussion, researchers explored the practical implications of existing game-theoretic models in understanding and treating cancer. They also highlighted the need for advancements in cancer biology to fully leverage the potential of these models. Ultimately, the application of evolutionary game theory in understanding tumor behavior was shown to have important medical implications, bridging the gap between real-world observations and mathematical modeling. The article concluded by examining evolutionary treatment approaches and their potential to extend life expectancy beyond that of traditional therapy. It suggested that evolutionary therapy could be more effective when dealing with pre-existing or therapy-induced resistant types. The main hurdle in integrating EGT treatment strategies in clinical settings is the challenge of precisely estimating tumor composition. Currently, this is only viable for specific cancer types. This treatment methodology is particularly effective for cancers where such information is obtainable.

2.3. Post Pandemic Educational Models

COVID-19 represents the much-anticipated global pandemic with the potential to severely impact both societies and economies, leading to widespread disruption. It's crucial to understand how COVID-19 unfolded as a health and development crisis, think about potential transformations after the pandemic, and reconsider development more broadly. Based on over a decade of research on epidemics, it was argued that analyzing the origins, progression, and effects of the COVID-19 pandemic requires addressing both structural political-economic conditions and less orderly, more unpredictable processes reflecting complexity, uncertainty, contingency, and context-specificity (Leach et al., 2021).

This duality in the conditions and processes of pandemic emergence, progression, and impact provides a way to understand three key challenge areas. The first challenge is related to how scientific advice and evidence are used in policy when conditions are firmly controlled by established power relations yet uncertain. The second involves how economies operate, as the COVID-19 crisis has revealed the limitations of conventional economic growth models. The third challenge concerns how new forms of politics can shape citizen-state relations in dealing with a pandemic, such as those centered around mutual solidarity and care and education.

Due to the pandemic crisis, educational institutions have been compelled to adopt new pedagogical approaches. This adaptation is imperative to mitigate the impact of the epidemic on the educational sector. While certain students may demonstrate proficiency in acclimating to the novel learning environment, the level of adjustment will undoubtedly vary among students, given that the majority are encountering this educational format for the first time (Heikkinen, 2023). Hence a new educational system has to be organized and EGT can help to researchers.

There is an important paper conducted by Accinelli et al. (2021). In this paper, researchers used tools from evolutionary game theory to analyze the evolution of the behaviors of professors, students, and schools in relation to the use of information and communication technologies (ICTs) in the teaching-learning process in the post-pandemic era. For this purpose, replicator dynamics were used, and it was shown that the solutions to this dynamical system could indicate the evolution that the teaching-learning processes will follow over time in the post-pandemic world.

In a recent study, Li and Wang (2022) utilized evolutionary game theory to investigate the management of primary and secondary school students' online learning during the COVID-19 pandemic. The study also aimed to assess the impact of stakeholders' behavioral choices on managing students' online learning. The researchers created two game models, "schools-students" and "schools-students-parents," and analyzed the influence of behavioral interactions on game equilibrium in these scenarios. Furthermore, researchers employed MATLAB 2018 software to conduct numerical simulations for their analysis.

The study revealed significant differences in strategy choices of students who play games and their management of online learning. It found that the main factor influencing students' strategic choices is the benefits they receive from learning. While involving parents can positively influence students' game strategy selection towards cooperation, there is a limit to their involvement. The study also found that the use of punishment or reward by schools does not significantly affect students' management of online learning. However, punishments and rewards from parents have a more significant impact on promoting students' strategic choices towards cooperation compared to those implemented by schools.

Muniz et al. (2023) utilized evolutionary game theory tools to analyze the evolution of the behaviors of professors, students, and schools in embracing the use of information and communication technologies (ICTs) for the teaching-learning process in the post-pandemic era. The replicator dynamics employed to illustrate potential solutions to this dynamic system, shedding light on the potential evolution of teaching-learning processes in the post-pandemic world over time.

They have implemented a teaching and learning model where professors, students, and authorities have the option to choose between traditional education, similar to the pre-pandemic era, or educational methods that integrate the use of Information and Communication Technologies (ICTs), capitalizing on the skills acquired during the COVID-19 pandemic. In game theoretical terms, this choice is seen as a three-player game, with each participant having two different strategies: supporting or opposing the use of ICTs in the teaching and learning process.

The authors demonstrated that the advancement of pedagogical methods is contingent upon the preferences of all stakeholders. The interplay among educators, students, and educational administrators shapes the progression of knowledge transmission and assimilation techniques. It is evident that embracing digital methodologies will necessitate commitment from educational authorities, teachers, and students.

In addition, this work has observed that the future direction of education in the post-pandemic era may be influenced by the decisions made by educational authorities regarding the use of ICTs. The choices made within schools will largely depend on the availability of economic resources and technological infrastructure. If large investments in ICTs are not deemed to be cost-effective, educational authorities may choose to revert to traditional offline education models. On the other hand, moderate investments in ICTs could be sufficient for professors to decide to undergo training and then facilitate the appropriate use of these available technologies by students. While the decisions of educational authorities greatly influence the direction of education, they are not the sole determining factors for the different scenarios to unfold, as all decisions are intertwined with other participants' preferences in the educational system.

Finally, researchers showed that the emergence of teaching cycles is possible. Incentives for the development of digital techniques must be maintained for a while because if they are eliminated, even when the use of these techniques is predominant, the process can be reversed and return to the initial situation.

In a significant study, Liu et al. (2023) developed a tripartite evolutionary game model involving schools, enterprises, and government to analyze the strategies of each party and the factors influencing them. The results revealed that the rewards for positive cooperation from sources other than the government mainly influence the stability of schools' and enterprises' strategies. On the other hand, the stability of the government's strategy is mainly influenced by the benefits of a positive cooperation strategy in the scenario where schools cooperate with enterprises. The study concludes with suggestions to enhance sustainable cooperation among schools, enterprises, and government.

The aforementioned research highlights the widespread use of evolutionary game theory methodologies in evaluating the efficacy of recently developed educational frameworks, especially in light of the global pandemic. The significant input of evolutionary game theory enables the modeling of both educational systems and the diverse range of individuals within these systems.

2.4. Network Theory

Network theory in evolutionary game theory (EGT) emphasizes the structure of interactions among agents within a network, where the arrangement of connections impacts the development of strategies. Networked systems frequently display intricate patterns, as the behavior of one agent can influence others, and these interactions evolve over time. In social networks, individuals, or nodes, are interconnected, and their interactions determine the dynamics of information or resource flow. Evolutionary Game Theory (EGT) models these interactions by examining the strategies individuals adopt in response to the behaviors of their peers.

EGT has been utilized to analyze competition and cooperation within economic systems, including trade and market dynamics. By representing businesses or countries as players in a network, evolutionary models can elucidate how competitive or cooperative strategies spread. For example, the evolution of market behaviors—such as price-setting or competitive bidding—can be explored within a network of economic agents interacting in a competitive landscape (Vega-Redondo, 2007).

In the view of infectious diseases, the integration of network theory with evolutionary game theory (EGT) models provides a framework to analyze the dynamics of disease transmission within populations. The interactions among individuals, conceptualized as agents on a network, critically influence the epidemiological spread of infections. Under specific conditions, cooperation mechanisms, such as vaccination, can emerge as stable strategies, promoting overall population health (Bauch & Bhattacharyya, 2012).

2.5. Cooperative Dynamics in Non-Biological Systems

Cooperation in non-biological systems, analyzed via Evolutionary Game Theory (EGT), explores the mechanisms through which agents engage in collaborative behaviors for collective gain. Within the framework of EGT, cooperative strategies emerge when the advantages of mutual collaboration surpass the associated costs. This dynamic is frequently influenced by the topology of the underlying network, which governs the interactions and payoffs between agents.

One significant application of evolutionary game theory (EGT) in cooperative dynamics is found in the view of global environmental agreements. By modeling the evolutionary dynamics of cooperation among nations facing climate change, we can elucidate how self-interested entities (or countries) might engage in cooperative behavior to address shared challenges, such as the reduction of carbon emissions. The core issue is ensuring that all parties commit to cooperation rather than resorting to defection, which can undermine collective efforts. Stable cooperative outcomes can be achieved through mechanisms that promote repeated interactions and robust enforcement strategies, as explored in Ostrom's work (1990).

In public goods games, participants are tasked with contributing to a shared resource that serves the collective. Yet, each individual is tempted to engage in "free riding," benefiting from the contributions of others without contributing themselves. Evolutionary game theory (EGT) models, particularly those employing the framework of evolutionary stable strategies (ESS), provide valuable insights into the dynamics through which cooperation can manifest under such conditions. The study of agents in networks interacting within public goods games is particularly compelling, as the characteristics of local interactions and the underlying network topology critically shape the dynamics of cooperative behavior (Bertschinger et al., 2011).

2.6. Challenges

The domain of EGT is rife with complexities and debates as scholars aim to construct precise models of real-world situations. One of the main difficulties lies in the intricate and varied behavioral patterns, preferences, and decision-making mechanisms exhibited by real individuals. Conventional rule-based techniques in agent-based modeling have constraints in encompassing the full spectrum of this diversity, requiring a more holistic method.

Ensuring a balance between model simplicity and accurate agent representation is critical, as oversimplification may overlook important aspects of agent heterogeneity. Therefore, there is a demand for more advanced methodologies that can effectively capture the diverse behaviors and decision-making processes of real-world individuals (Gao et al.,2023).

The current techniques for simulation integration necessitate the incorporation of multiple dimensions of simulation. These dimensions involve the description of systems under known conditions, the explanation of emergent patterns, the prediction of future states, and the exploration of hypothetical scenarios. Rule-based methods are effective in solving descriptive problems, while symbolic or stochastic methods elucidate underlying mechanisms. Machine learning models are adept at predictive tasks, as they can identify concealed patterns in data; however, they are associated with lower interpretability. This disparity poses a significant challenge in the development of models that harmoniously combine behavioral accuracy, interpretable mechanisms, adaptability, and reliability in evolving environments.

One another important consideration is the limitations of current models in supporting integrative simulations for real-world problems. For example, agents based on Large Language Models (LLMs) can capture complex internal characteristics and specialized traits using techniques such as prompting, in-context learning, or fine-tuning. However, these methods still have limitations when simulating realistic processes or systems, which highlights the need for further development in this rapidly evolving field.

Integrating artificial intelligence (AI) with evolutionary game theory (EGT) also faces several challenges. Biological and social systems in the real world are inherently dynamic and stochastic, which presents significant challenges for AI algorithms that utilize evolutionary game theory (EGT) for predictive modeling. While simplifications are often necessary for computational efficiency, such reductions can constrain the applicability and fidelity of the models (Bukkuri & Brown, 2021; Blume & Easley, 2006). One another significant challenge is the limitations and representation of data. AI systems necessitate comprehensive, high-quality datasets to inform EGT (Evidence Generation and Translation) models effectively. Insufficiently populated or biased datasets can severely undermine the accuracy of predictions, especially in tailored applications such as cancer therapeutics (Dong et al., 2020).

Interpretability and clinical integration present significant challenges in the field of artificial intelligence. To align AI-generated electrocardiogram (EGT) predictions with clinical protocols, it is essential for these predictions to be interpretable and usable for decision-makers. Complex models can produce outputs that are difficult to understand and act upon (Newton, 2012; Gou & Deng, 2021). Moreover, ethical concerns are paramount. The use of patient-specific data in AI-EGT applications raises issues related to privacy, informed consent, and bias, particularly in healthcare settings. One last significant challenge associated with AI systems integrated with Evolutionary Game Theory (EGT) is the substantial computational expense, especially when scaling these systems to accommodate the adaptive and interactive characteristics of agents (Fan & Hui, 2020).

The current EGT models have also critical limitations when it comes to supporting integrative simulations for real-world problems due to their inability to effectively address the complexities and multifaceted nature of these problems. While LLM agents are capable of capturing complex internal characteristics and specialized traits through techniques like prompting, in-context learning, or fine-tuning, they still struggle when it comes to simulating realistic processes or systems. This indicates a clear need for further advancement in this rapidly evolving domain. The complexity of these challenges highlights the crucial importance of the audience's work in this field. Evolutionary explanations of social norms use models that explicitly demonstrate value commitments and derive other normative commitments from the actions of self-interested agents with limited rationality. This approach offers clarity and reveals the logistical assumptions necessary for manageability, which can affect the model's results if not handled carefully. Assumptions such as random mating, an infinitely large population size, and nonoverlapping generations are common in many population genetic models and are used to simplify the complexity without fundamentally altering the outcomes.

One last controversial point of contention involves the utilization of simplified and abstract models to directly compare them with the EGT problem, instead of accurately representing real-life scenarios. The use of utility-based proportional reproduction methods instead of more realistic reproduction scenarios is a clear example of this approach, emphasizing the delicate balance between the simplicity of the model and its real-world accuracy.

3. FUTURE DIRECTION

Evolutionary game theory is an incredibly diverse and interdisciplinary field that expands well beyond the boundaries of traditional biology. It acts as a magnet for mathematicians who are captivated by the elegance of simple evolution models, leading them to delve into other areas of evolutionary biology and ecology. In a similar vein, social scientists perceive the value of evolutionary thinking and apply biological insights to their own research. Furthermore, computer scientists bring their expertise by employing algorithms to explore a novel domain where machines not only learn from their environment but also from each other.

The expansive reach of the field and its emphasis on popular concepts such as cooperation do present a challenge: comparable insights are frequently rediscovered in differing fields utilizing distinct terminology and modeling techniques. For example, notions like reciprocity or spatial structure may be interpreted divergently. Will these distinct branches persist in advancing separately, or will they coalesce into a cohesive set of ideas, traditions, and software repositories? Alternatively, will these disciplines continue to engage and draw from one another, cultivating a beneficial exchange between them? The allure of evolutionary game theory not only rests in its capacity to explain but also in the intuitive essence of its models.

Recent advancements in the field have highlighted the integration of agent-based and complex network-based models. This innovative approach emphasizes the importance of considering the diversity, interconnectivity, and interactions among agents to enhance system resilience. The need for a cohesive framework for modeling complex adaptive systems has been reinforced through various multidisciplinary case studies.

In addition, the widespread use of large language model (LLM)-driven agents has greatly impacted the advancement of evolutionary game theory. Open-source platforms like Voyager and XAgent have made significant progress in breaking down tasks and strategic planning. These platforms demonstrate the capacity of LLMs to adjust their strategies dynamically by incorporating ongoing feedback and changing scenarios. This ultimately improves decision-making and problem-solving efficiency.

Research has also highlighted the potential for machine learning-based agents to effectively model various aspects of human behavior, such as economic activities, social interactions, and decision-making processes within highly complex and realistic environments. Furthermore, the intersection of evolutionary game theory with practical, real-world applications presents a rich opportunity for further investigation and exploration.

Specifically, there is significant potential for LLM-based agents to accurately model and replicate economic activities, social behaviors, and complex decision-making processes within realistic environments. This convergence presents an intriguing and promising area for future investigation and application.

Lastly, population geneticists and evolutionary game theorists are collaborating to explore promising avenues for future research. By integrating concepts and methodologies from these two fields, researchers aim to enhance the explanatory power and intuitive nature of evolutionary game theory models. This exchange of ideas is expected to lead to a unified framework that can offer deeper insights into the dynamics of evolution and population genetics.

Here are some questions about the future of evolutionary game theory (EGT):

- How will the integration of machine learning and artificial intelligence further enhance the predictive capabilities of evolutionary game theory?
- What new methodologies can be developed to address the complexities of modeling large-scale, interconnected systems in evolutionary game theory?
- How can evolutionary game theory be applied more effectively to real-world applications such as healthcare, economics, and social behavior?
- What role will interdisciplinary collaboration play in the future evolution of EGT, particularly with fields like network theory and behavioral science?
- How will the field of evolutionary game theory evolve in the context of rapidly advancing computational power and data analytics?

In conclusion, the future of evolutionary game theory (EGT) appears promising, with significant advancements anticipated through the integration of AI, machine learning, and interdisciplinary collaboration. As computational tools continue to evolve, the predictive power of EGT is expected to expand, particularly in practical applications such as healthcare, economics, and social behavior. The convergence of EGT with network theory and population genetics presents exciting opportunities for a deeper understanding of complex systems. However, overcoming the associated challenges will require the development of innovative methodologies and the promotion of robust interdisciplinary exchanges, ensuring that EGT remains a dynamic and evolving field ripe for future exploration.ion.

4. CONCLUSION

In conclusion, EGT is a highly influential and continually developing framework that utilizes game-theoretic principles to analyze intricate interactions within biology, economics, and the social sciences. Initially advanced by John Maynard Smith, EGT has transcended its origins in biology to profoundly impact diverse fields, showcasing its adaptability and robust analytical prowess.

EGT is rooted in robust theoretical foundations and heavily relies on mathematical modeling and replicator dynamics to study the development of strategies within a population over time. These models are valuable for predicting behavioral outcomes from initial conditions and have wide-ranging applications in fields such as evolutionary biology and macroeconomic analysis. The integration of large language models like GPT-3.5 and GPT-4 into agent-based simulations represents a significant advancement, enabling the creation of sophisticated, human-like agents capable of navigating complex strategic landscapes with greater realism. This shift towards more intricate modeling captures the subtleties of human behavior and decision-making, leading to deeper insights into economic and social interactions.

Even with technological advancements, EGT encounters major hurdles in accurately representing the diverse range of agents and their decision-making processes. Conventional simplifications have constraints that may result in oversights when modeling complex adaptive systems. Furthermore, effectively integrating different simulation dimensions - descriptive, explanatory, predictive, and exploratory - is a significant challenge in creating comprehensive models that mirror real-world dynamics.

Future directions for EGT are rich with potential, especially as researchers continue to explore the intersections of population genetics and game theory, fostering collaborations that can unify concepts and methodologies. The incorporation of LLM-driven agents into agent-based modeling promises to break ground in simulating real-world phenomena, bridging gaps between theoretical insights and practical applications. This convergence not only enhances our understanding of evolutionary dynamics but also contributes to solving pressing societal challenges, from healthcare to education and beyond.

As research in EGT progresses, it is crucial for scholars to not only engage with the theoretical advancements in the field but also to consider the practical implications of their work. The continuous exchange of ideas across various disciplines and the refinement of modeling techniques are expected to play a central role in influencing the future trajectory of EGT. This will help to maintain the significance and real-world applicability of EGT in an ever-changing and intricate global context.

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