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PhD Thesis Report

Report of a reviewer for dissertation thesis by **Martin Schimd**
"Search in Imperfect Information Games"

The topic of the thesis

Games are one of the common benchmarks for algorithms and artificial intelligence in general. Many of the milestones of artificial intelligence are demonstrated by designing and implementing an algorithm that successfully wins in a match against a top human player. Examples include checkers, chess and famous DeepBlue, and recent AlphaGo. The reviewed thesis describes components that contributed to a similar milestone – designing and implementing a new type of search algorithm that was the key for the program DeepStack that successfully won against 33 professional human players in the game of poker in 2016.

The key part of DeepStack is a novel, sound search algorithm for sequential games with imperfect information, such as poker. In this thesis, Martin Schmid describes research challenges that were required to solve, in order to design the novel search algorithm. The contributions described in this thesis can be seen as a culmination of 10 years of research of the community in imperfect information games. The highest importance and significance of this research is demonstrated by the fact that the main result – DeepStack – has been published in Science.

Structure and content of the thesis

The thesis is divided into two main parts – sequential games with perfect information (Part 1) and sequential games with imperfect information (Part 2). While the contributions are mostly focused on imperfect information games, describing the problems in perfect information games first amplifies the differences and difficulties that arise when players do not perfectly observe the game. The first chapters (Chapter 2 – 5) introduce the formal definitions of sequential games and necessary concepts (such as strategies and their optimality). Afterward, the thesis describes different algorithms while distinguishing between offline (equilibrium computation) algorithms (Chapter 6) that solve the game at once and online (game playing) algorithms that seek a strategy to be played online during the gameplay (Chapter 7). Search algorithms in games (typically) belong among online algorithms and the thesis proposes a relation between (approximate optimal) offline algorithms and sound online algorithms by defining a number of levels of consistency for online strategies. Finally, a specific chapter is devoted to the search in perfect information games (Chapter 8) discussing basic components of search algorithms in game trees, such as decompositions and using approximate value functions.

The structure of the second part is similar, however, the chapters are described in more details as they contain most of the contributions. One of the contributions is a proposition of a new formalism for modeling sequential games with imperfect information (Chapter 13). Instead of commonly used formalism termed extensive-form games (EFGs), Martin (and co-authors) propose Factored-Observation Stochastic Games (FOSGs) – a variant of more general partially-observable stochastic games. The key difference is in using observations, which are not explicitly defined in EFGs, and that define the knowledge of players throughout the game. The following chapters then again focus on strategies (Chapter 14) and issues when decomposing games

with imperfect information (Chapter 15), finally moving to different types of offline algorithms (Chapters 16 to 18) and online algorithms (Chapter 19) and to search (Chapter 20). The final chapter, Chapter 21, then describes DeepStack itself.

Evaluation

The quality of the scientific results summarized in the reviewed thesis is exceptional. Besides the already mentioned Science publication, the results were also accepted to highly selective conferences in artificial intelligence (such as AAAI and AAMAS) and another high-quality journal (Journal of Artificial Intelligence Research – JAIR). It is clear that Martin Schmid has made a significant contribution to the field of artificial intelligence and computational game theory.

The thesis itself is written generally well, there are many examples demonstrating key principles and counterexamples that arise when solving/playing imperfect information games. I have only minor comments and remarks to the text:

1. The technical/mathematical level of details in the thesis is somewhat inconsistent. While some theorems are proved in the thesis (even though they are, for example, well-known results appearing in game-theoretical textbooks and it is not clear why a proof should be repeated here, e.g., Theorems 4, 5, etc.), some proofs that are part of the technical contribution of this thesis are missing and referred to supporting publications. Unifying the level of details (e.g., by having all proofs at least as a technical appendix to the thesis) would improve the formal quality of the text.
2. The work sometimes makes remarks to related research, but the details remain unexplained so that even a well-informed reader has a hard time appreciating the remark and must follow the reference (e.g., certificates in imperfect information games, CFR-D and Stackelberg equilibria, etc.). Removing such remarks or expanding them in a separate section would improve the readability.
3. Slightly more attention can be paid to framing the research in related work from the perspective of game theory and stochastic games (especially due to the proposition of the new formalism FOSGs). Stochastic games with private/public actions/observations appeared in the literature before (e.g., Cole & Kocherlakota, Dynamic games with hidden actions and hidden states, 2001) as well as the framing of the online algorithm as a repeated game, qualitative performance of different strategies can be related to Range of Skill (Zinkevich et al. 2007, Hansen et al. 2008), etc.

My final remark is to the list of contributions of the thesis. Since many of the publications that support the technical contributions of this thesis are co-authored by other PhD students (Matej Moravcik, Michal Sustr) that are also often the first (primary) authors of these publications, it would be good to clarify the details of individual contributions.

In conclusion, I believe that the PhD thesis of Martin Schmid is an excellent contribution to the theory and algorithms solving and playing large imperfect information games and support accepting this thesis and awarding Martin Schmid with PhD degree.

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