Maastricht University

Faculty of Humanities and Sciences

Project title: Combinatorial Game Theory & Artificial Intelligence

Project leader: Dr. J.W.H.M. Uiterwijk

Function: Associate Professor at the Department of Data Science and Knowledge Engineering (DKE), Maastricht University, Maastricht, the Netherlands

Collaborators: Prof.dr. R. Nowakowski, Prof.dr. F. Thuijsman, dr. G. Schoenmakers

Proposal:

Introduction: Artificial Intelligence (AI) research has put much effort in designing dedicated search algorithms for complex games. This has led to many strong techniques, e.g., based on αβ, proof-number (PN) search and Monte-Carlo Tree Search (MCTS). However, for complex *combinatorial games*, most of these algorithms perform rather weak. Whereas the Combinatorial Game Theory (CGT) provides the means to determine precise game-theoretic values of such games, most algorithms are unable to incorporate them in an efficient and effective way. Preliminary research using the games Domineering and Clobber demonstrated that this type of research combining CGT and AI techniques can be very fruitful though (see selected publications 2-5).

Hypothesis and Objectives: The current research proposal addresses the problem of designing new and enhancing existing algorithms with knowledge obtained from CGT. The research will address the following four research questions:

1) How can we efficiently calculate and store CGT values for combinatorial games?
2) How can we incorporate these values into existing search strategies?
3) How can we design new search strategies which are specifically designed for combinatorial games?
4) Can we further develop parts of CGT using insights and results from AI?

Setting and Methods:

As a consequence of the fact that CGT values are not just indications who wins a game, but are explicit recursive representations of the positions reachable by each player, it is far from obvious how they can be stored. We envision devising methods that enable an efficient and effective method of storing them.

To incorporate CGT values into existing search strategies, several methods will be explored. Regarding αβ, we intend to use CGT values (as a component) in the evaluation function and for move ordering, and to decide how deep lines will be investigated (both in forward-pruning lines and in extending promising lines). Regarding MCTS-based programs we will investigate how to use the values to guide the *selection step* (balancing exploration and exploitation of the search tree), and how to use the values in the *playout step* (guiding the pseudo-random moves in the simulations).

We believe that it will also be beneficial to devise new search strategies tailored to CGT. Such strategy can be a variant of Proof-Number (PN) search that, instead of minimizing the effort to prove or disprove a binary goal, will take into account the internal structure of CGT values to minimize their complexity. Other new search strategies involving CGT are expected.

Since the CGT is a relatively young theory, a last aim is that the development of search-based strategies involving CGT will enhance and extend the theory, both game-dependently (like already done for Domineering) and game-independently. Many opportunities are foreseen to arise.

Impact: Although the programs and the techniques to be developed will be specifically designed for combinatorial games, the insights and general principles obtained will be of interest for other complex problem-solving domains. Especially the combination of perfect knowledge like CGT values with heuristic (evaluation-based) or statistical (Monte-Carlo) techniques has wide applications. Areas include stock-market prediction, general optimization and long-range planning (like manufacturing and airline scheduling) and agent-based applications (like automated negotiation).

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Requirements candidate: Highly motivated student with good English communication skills and proactive and resolute attitude. Moreover, good programming skills are a precondition.

Keywords: Combinatorial Game Theory, Artificial Intelligence, Intelligent Search Strategies

Top 5 selected publications:

1. Herik, H.J. van den, Uiterwijk, J.W.H.M. and Rijswijck, J. van (2002). Games Solved: Now and in the Future. *Artificial Intelligence*, **134**(1-2) 277-311.
2. J.W.H.M. Uiterwijk (2014). Perfectly Solving Domineering Games. In *Computer Games, Workshop on Computer Games, CGW at IJCAI 2013, Beijing, China, Revised Selected Papers* (eds. Cazenave, Winands and Iida), *Communications in Computer and Information Science* **408**, pp. 97-121, Springer Int. Publ.
3. J.W.H.M. Uiterwijk and M. Barton (2015). New Results for Domineering from Combinatorial Game Theory Endgame Databases. *Theoretical Computer Science* **592** 72-86.
4. J.W.H.M. Uiterwijk (2016). Polymerization and Crystallization of Snowflake Molecules in Domineering. *Theoretical Computer Science* **644** 143-158.
5. J.W.H.M. Uiterwijk and J. Griebel (2017). Combining Combinatorial Game Theory with an Alpha-Beta Solver for Clobber: Theory and experiments. In *BNAIC 2016: Artificial Intelligence, 28th Benelux Conference on Artificial Intelligence, Amsterdam, The Netherlands, November 10–11, 2016, Revised Selected Papers* (eds. Bosse and Bredeweg), *Communications in Computer and Information Science* **765**, pp. 78-92, Springer Int. Publ.

Other relevant publications:

- M. Barton and J.W.H.M. Uiterwijk (2014). Combining Combinatorial Game Theory with an α-β Solver for Domineering. In *BNAIC 2014: Proceedings of the 26th Benelux Conference on Artificial Intelligence* (Eds. Grootjen, Otworowska and Kwisthout), pp. 9-16, Radboud University, Nijmegen.
- J.W.H.M. Uiterwijk (2014). The Impact of Safe Moves on Perfectly Solving Domineering Boards – part 1: Analysis and Experiments with 1-Step Safe Moves (*ICGA Journal* **37**(2) 97-105); part 2: Analysis and Experiments with Multi-Step Safe Moves (*ICGA Journal* **37**(3) 144-160); part 3: Theorems and Conjectures (*ICGA Journal* **37**(4) 207-213).
- J.W.H.M. Uiterwijk (2015). Crystallization of Domineering Snowflakes. In *Proceedings of Advances in Computer Games 2015 Conference* (*ACG15*) (Eds. Plaat, Van den Herik and Kosters), *Lecture Notes in Computer Science* **9525**, pp. 100-112, Springer Int. Publ.
- J.W.H.M. Uiterwijk (2016). 11 x 11 Domineering is Solved: The First Player Wins. In *Proceedings of the 9th International Conference on Computers and Games* (*CG2016*) (Eds. Plaat, Van den Herik and Kosters), *Lecture Notes in Computer Science* **10068**, pp. 129-136, Springer Int. Publ.
- J.W.H.M. Uiterwijk (2017). Set Matching: An Enhancement of the Hales-Jewett Pairing Strategy. To appear in *Proceedings of the 15th International Conference on Advances in Computer Games 2017* (Eds. Winands, Van den Herik and Kosters), *Lecture Notes in Computer Science*, Springer Int. Publ.