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than $1, 2, \ldots, i$. As same as "8" in DAIHINMIN, no card is stronger than a card with $\tilde{i}$ for $i = 1, \ldots, n$. In this sense, the cards in 8-cut rule TANHINMIN are in total preorder except cut cards.

The following is the main theorem of this paper.

Theorem 1. *In 2-Player TANHINMIN with n cards, one can decide which player has a winning strategy any time at the game in SORT + $\mathcal{O}(n)$ time, where SORT is the time to sort the cards of each player.*

We also obtain the following for 8-cut TANHINMIN.

Theorem 2. *In 2-Player TANHINMIN, including the "8-cut" rule, with n cards, one can decide which player has a winning strategy in SORT + $\mathcal{O}(n)$ time, where SORT is the time to sort the cards of each player.*

These algorithms are based on a graph representation of an instance of TANHINMIN, and they compute several parameters of the graph which are used to judge which player is the winner. Note that computation can be done in $\mathcal{O}(n)$ time without constructing the graph, if the cards of each player are sorted.

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Tile Pattern-Building Games on a Grid are PSPACE-complete

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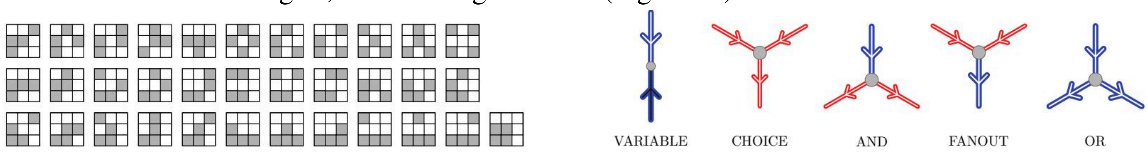
In this paper, we investigate a certain class of tile-based pattern games through a simplified version of a recent game titled Nonads. We prove that Nonads is PSPACE-complete with a reduction from bounded 2-player constraint logic (Bounded 2CL) even when both players share the same target and there is only one type of playable tile. This has application to any grid-based pattern building game.

Introduction

Games have always been an enjoyable area of research and a stepping stone to more serious problems. Many areas of research began or significantly grew from interesting puzzles and game strategies such that Martin Gardner's "Mathematical Games" column in *Scientific American* was the most popular feature for over 25 years, and there are numerous books dedicated to these types of problems. We look at a 2-player game based on pattern construction from a fixed set of playable tiles, and show that a simplified version of the 2-player game Nonads [1] is PSPACE-complete using a reduction from bounded 2-player constraint logic (2CL) [3]. Nonads uses the same tile-set and has some relation to other games such as NOVI [2] and the Haar Hoolim Perception Games [4].

Nonads. Nonads is a simple pattern building game created by Cameron Browne [1] consisting of 34 *nonad* tiles, which are 3×3 squares containing 4 black and 5 white cells. There are 34 unique ways to color four cells in a 3×3 grid, not counting rotations (Figure 1a).



(a) The 34 Nonad tiles (b)

Figure 1: (a) Pieces for Nonads consisting of 2-colored (4 black and 5 white) 3×3 grid tiles. (b) Gadgets that must be implemented to reduce from bounded 2-player constraint logic.

Setup. At the beginning of the game, each player draws a "target" tile pattern they must build by assembling together the playable tiles. One random tile is taken from the set and used as the center piece of the board. *Play*. Players take turns placing a tile adjacent to at least 1 cell of a previously placed tile (no floating tiles). Tiles cannot overlap and are played on an implied grid based on the center tile. *Win*. The first player to assemble their target pattern (in any rotation) wins the game. Empty spaces do not count towards a pattern.

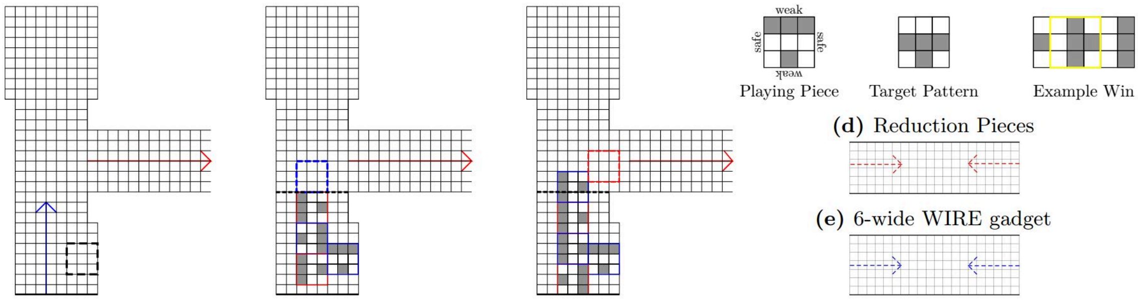
Constraint Logic. An instance of bounded 2-player constraint logic (2CL) is a constraint graph G, a partition of the edges of G into sets B (Black) and W (White), and edges $e_B \in B$, $e_W \in W$. If the players alternate making legal moves where White/Black may only reverse edges in their set (W/B), knowing whether White can ever reverse e_W is PSPACE-complete [3]. Figure 1b shows the gadgets that must be implemented in order to reduce from 2CL.

Nonads Complexity

A generalized version of Nonads is a set of *pieces* where each is a 2-colored tile as in Figure 1a played on an implicit *board* $n \times n \subset \mathbb{Z}^2$. Each player has a 3×3 *target* pattern, and players take *turns* placing pieces on the board. Does there exist a forced win for player 1 given a configuration of pieces?

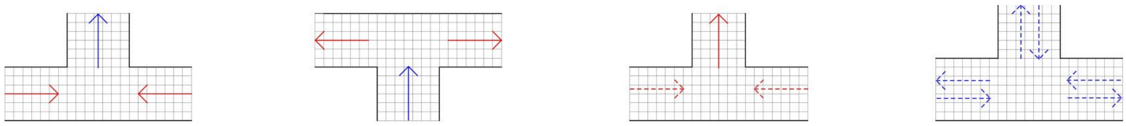
Tiles. Since Nonads allows arbitrary placement on the board, we must restrict the players' choices to correctly use the gadgets. A win condition is dependent upon the target tile and next available piece. The players have the same target tile, along with an unbounded play sequence of just one tile type. The configuration requires both players to play optimally or the other player will win. Figure 2d shows the playing tile (Playing Piece)- meaning each player will always be playing a copy of the same tile. For the reduction, both players also have the same target (Target Pattern). Two playing pieces are required to match the target pattern (Example Win). However, since both players have the same target pattern, exposing the *weak* sides of any player's playing tile will open up a potential win for the next player. Thus, each player must place their piece in a way that is defending the weak sides of the tile, and only exposes the *safe* sides of the tile. This way, both players must play in specific ways within the gadgets.

WIRE Gadgets. Figures 2e and 2f show the two versions of the WIRE gadget. These different width wires connect to the inputs/outputs of the gadgets. In terms of constraint logic, 6-wide corridors (red) represent weight-1 edges while 7-wide corridors (blue) represent weight-2 edges. The different arrows represent the "flow" through the gadget. The arrows are dotted, because either direction can be selected. The other gadgets are combinations of these two WIRE gadgets. The "walls" of the gadgets are non-empty and built with tiles containing no helping pattern for the target. Since the playing pieces have two weak sides and two safe sides, the wire gadgets are traversed if and only if the two weak sides are



(a) VARIABLE gadget (b) FALSE offset (c) TRUE offset (d) Reduction Pieces (e) 6-wide WIRE gadget (f) 7-wide WIRE gadget

Figure 2: (a) Initial move in the variable gadget (b) To create a 'false' input, a player must place their tile so that the last tile played gives a 0-offset to the corridor. This disallows further play in this corridor, as any move would result in a victory for the opposing player. (c) A 'true' input is only possible when the offset is 2 and the next player can place their tile in the red dashed box that protects both weak sides. (d) Pieces used in the reduction. (e) Hallway of width-6 equal to a weight-1 edge in a constraint graph. (e) Hallway of width-7 equal to a weight-2 edge in a constraint graph.



(a) AND gadget (b) FANOUT gadget (c) OR gadget (d) CHOICE gadget

Figure 3: (a) AND gadget (b) FANOUT gadget (c) OR gadget (d) CHOICE gadget

not exposed, i.e., a tile played against a wall exposes a weak side.

VARIABLE Gadget. The variable gadget (Figures 2a, 2b, and 2c) allows players to set true or false inputs. The only initial safe place to play and start the game would be where the black dotted box is in Figure 2a. The next player can then place a tile at the bottom of the variable gadget or place in another variable gadget. Thus, both players may choose to set a variable. A player has one spot available at an unused variable gadget, but has multiple options after the first tile has been placed. The positioning of the second tile determines the truth assignment of the gadget and then sends it down the wire. The offset of the last tile before the opening dictates true or false.

AND/FANOUT Gadgets. In Figures 3a and 3b the colored arrows depict weighted edges (from 2CL), but the solid arrows represent forced edges. The direction is forced between plays. One change affects all other edges. For the AND gadget, tiles must be placed in BOTH of the corridors with the red arrows before pieces in the corridor with the blue arrow; they will lose if they try to turn the corner too soon. The FANOUT gadget is a reversed AND gadget. Tiles incoming from the blue corridor can turn and depart out of both of the red corridors.

OR/CHOICE Gadgets. In Figures 3c and 3d the arrows again represent weighted edges. The OR gadget has one dedicated "out" edge. Since this gadget consists of all 6-wide corridors, at least one of the dotted red arrows is required as input. Tiles need to be placed in at least one of the inward facing corridors before they can start being placed in the outward-heading corridor. The CHOICE gadget is similar to the OR, but the outward facing edge can be freely chosen. An input into any of the corridors will allow output to either of the other two. This is due to the 7-wide corridors which represent weight-2 edges.

Theorem 1. *Nonads is PSPACE-complete with only one playing piece and identical targets.*

Proof. Given a bounded planar 2CL graph, we construct a corresponding Nonads position as described above. This reduction takes polynomial time. Player 1 can win the resulting Nonads game if and only if they can win the 2CL game (flip a specified edge). For membership in PSPACE, since the game will end after a polynomial number of moves, it is possible to perform a search of all possible move sequences using polynomial space, thus determining the winner. Thus, Nonads is in PSPACE.

Conclusion

We have shown that Nonads, a pixel-based tile pattern game of with 3×3 size pieces, is PSPACE-complete even with only one playable piece and identical target patterns for the players. Is this still true with aligned pieces (pieces must fully align an edge with an adjacent piece edge)? Is this true with a smaller 2×2 piece and target?

Acknowledgments. This research was supported in part by National Science Foundation Grant CCF-1817602.

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Barnette's Conjecture through the Lens of the Mod_kP Complexity Classes

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In circa 2006, Feder & Subi established that Barnette's 1969 conjecture, which postulates that all cubic bipartite polyhedral graphs are Hamiltonian, is true iff the Hamiltonian cycle decision problem for this class of graphs is polynomial time solvable (assuming $P \neq NP$). Here, we bridge the truth of Barnette's conjecture with the hardness of a related set of decision problems belonging to the Mod_kP classes (not known to contain NP), where we are tasked with deciding if an integer k fails to evenly divide the Hamiltonian cycle count of a cubic bipartite polyhedral graph. In particular, we show that Barnette's conjecture is true if there exists a polynomial time procedure for this decision problem when k can be any arbitrarily selected prime number. However, to illustrate the barriers for utilizing this result to prove Barnette's conjecture, we also show that the aforementioned decision problem is Mod_kP-complete $\forall k \in (2\mathbb{N}_{>0} + 1)$, and more generally, that unless $NP = RP$, no polynomial time algorithm can exist if k is not a power of two.

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