KAMI: Leveraging the power of crowd-sourcing to solve complex, real-world problems

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***Abstract*—Many of the complex problems facing the world today have been formally classified as what computational theorists call NP-complete problems, meaning problems for which no known algorithm exists for optimally solving the problem in a tractable time frame. On the other hand, humans often demonstrate a unique adeptness at being able to solve NP-complete problems. In this paper, we propose using the popular flood fill game KAMI as a crowd-sourced platform for representing arbitrary NP-Complete problems to human users. More than simply a game of problem-solving or strategy, KAMI derives its success from the fact that each puzzle is an artistic artifact whose popularity depends as much on the creative rendering of the problem as much as the challenge or intrigue of the problem itself. We discuss how the principles of computational creativity represent the key to representing NP-complete problems in this medium so as to be able to effectively harness the power of human problem-solving via crowd-sourcing methods.**

***Index Terms*—Computational theory, NP-completeness, crowd-sourcing, games**

I. Introduction

As the winner of multiple Editors' Choice awards, KAMI boasts a player base in the tens of thousands. As a one-player combinatorial game with an engaging puzzle experience, KAMI may simultaneously hold a secret that would allow it to function as a powerful tool enabling computer scientists, doctors, and engineers to solve some of the world's most complex problems: NP-complete problems. NP-complete problems are uniquely characterized by the fact that most NP-complete problems cannot be solved in a tractable time frame by modern day computers. They are also uniquely characterized by the fact that all NP-complete problems can be converted (in a tractable time frame[1]) into the representation of any other NP-complete problem, allowing solutions to one such problem to satisfy instances of other NP-complete problems.

Consider for example, the infamous Traveling Salesperson problem (i.e., "Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?"). This problem can (in tractable time) be reduced to instances of graph coloring problems, boolean satisfiability problems, set cover problems and virtually an infinite number of other problems that routinely crop up in real-world contexts. An efficient solution to any of these problems stands to benefit societies and organizations in untold ways [1]. It is important to note that while the solutions to these problems can be verified in polynomial time, the reason they are classified as NP is because the problems themselves cannot be solved in polynomial time (NP stands for "non-polynomial"). NP-Complete problems have the same properties that NP problems do with the exception that every existing NP problem must be reducible to it in polynomial time. This is a property that regular NP problems don't have. Many notable examples of NP-Complete problems can be observed in Richard Karp's 1972 paper "Reducibility Among Combinatorial Problems" [2]. Practical examples of NP-complete problems are virtually everywhere in the modern world: scheduling problems [3], genome assembly and scaffolding [4], cloud-computing [5], resource allocation [6], powergrid computing [7], water flow planning [8], route planning, dependency planning, organizational behavior, and on and on.

As a flood fill game, a KAMI puzzle itself represents an instance of an NP-Complete problem [9]. But unlike many NP-complete problem representations, tens of thousands of mobile game players willingly devote countless hours and money in the pursuit of designing and solving KAMI puzzles. What makes this particular form of NP-complete puzzle so alluring is that puzzles are creatively and artistically designed to be novel, interesting, intentional, and surprising—in short, KAMI puzzles are considered creative artifacts. In this paper we present an initial hypothesis on how the principles of computational creativity (CC) can be applied in the context of rendering arbitrary NP-complete problems as KAMI puzzles in order to leverage the massive KAMI crowd-sourcing platform to effectively solve real-world problems. Critically, this paper will serve as a pilot to future research we intend to conduct which would allow us to evaluate this hypothesis.

The idea of using crowd-sourcing to solve problems too complex for modern computers has been only recently explored, particularly in domains such as bioinformatics and quantum computing. Foldit is an online puzzle video game about protein folding (a notoriously difficult problem in bioinformatics) that leveraged a player base of 57,000 players to obtain useful results that matched or outperformed algorith-

[1] i.e., in polynomial time

Fig. 1. KAMI puzzles are characteristically artistic and creative. Finding optimal solutions to a KAMI puzzle via computational means is an NP-complete problem.

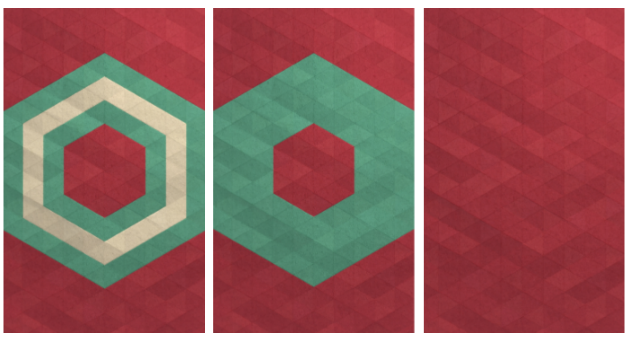

Fig. 2. Each KAMI puzzle presents itself as a multi-colored plane. The player makes a move by replacing a colored section of the graph with a color of their choice (e.g., replacing white with green). The goal of the game is to make the entire plane monochromatic in the fewest possible moves.

mically computed solutions [10]. More recently, researchers in the domain of quantum computing introduced a citizen science game, Quantum Moves 2, and found that players were able to optimize solutions roughly on par with the best of the tested standard optimization methods performed on a computer cluster [11]. This area of study has been called "human computing" and is a topic of study in the field of Human-Computer Interaction (HCI) [12].

II. KAMI Puzzle Representation

KAMI is an origami-inspired puzzle game that presents players with creative geometric patterns (see Fig. 1). The creativity of the puzzles inspires players to work diligently to find optimal solutions to a puzzle. An optimal solution to a KAMI puzzle is a minimum sequence of moves that would transform the puzzle into a monochromatic plane (see Fig. 2). It's creative appeal has garnered a player base in the tens of thousands, something fundamental for crowd-sourcing.

A. Representing a KAMI puzzle as a Graph

A KAMI puzzle can be reduced to a simplified representation of the same problem as a colored graph (see Fig. 3). A KAMI puzzle P can be converted to an identical graph G according to the following algorithm:

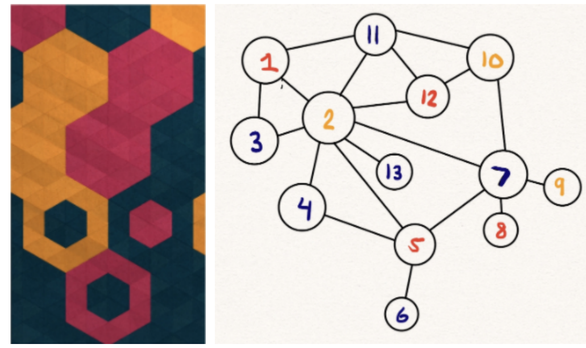

Fig. 3. We can use the graph on the right to represent a simplified version of the KAMI puzzle on the right. There is a many-to-one relationship between KAMI puzzles and their simplified graphical representations.

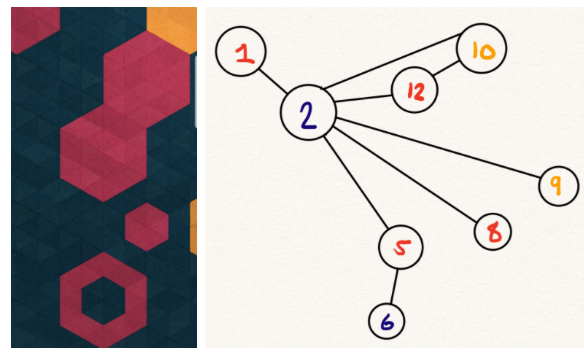

Fig. 4. The above KAMI puzzle and its associated colored graph are the result of starting from Fig. 3 and making the move of changing node 2 from yellow to blue.

- Each continuous monochromatic subregion of color in P, no matter its size, is shown as a single node in G of the same color.
- An edge exists between each pair of nodes in G for which their corresponding colored regions in P are adjacent.

As multiple KAMI puzzles can be simplified to the same graph, there exists a many-to-one relationship between KAMI puzzles and their simplified graphical representations.

Conversely, any colored graph G with the following three characteristics has at least one equivalent KAMI puzzle.

- G must be finite
- G must be colored
- G must be undirected

A *move* can be played on a colored graph G by selecting a node $N \in G$ and performing the following:

- Change the color of N to a color of your choice C.
- If any two adjacent nodes N and N' are of the same color, add the neighbors of N' to become neighbors of N and remove N from G.

An example of a valid move, starting from Fig. 3 and then changing node 2 from yellow to blue, is shown in Fig. 4.

A KAMI solution for a given graph can be defined as any sequence of moves that results in a monochromatic graph with exactly one node. Its decision problem variant asks if a k-move sequence exists that turns the graph monochromatic.

The optimal solution is the solution with the shortest sequence of moves. Finding the optimal solution is an NP-complete problem [9].

The fact that a single graph can encode the basic problem for many different puzzles creates an interesting challenge: *Given an arbitrary colored graph representing an arbitrary NP-complete problem, what is the most creative (i.e., novel, valuable, surprising, intentional) KAMI puzzle that can be used to represent that graph?*

The process of formally reducing an arbitrary NP-complete problem into an equivalent colored graph is beyond the scope of this initial foray into the domain.

III. A Deeper Significance?

The question arrived at in the last section represents an important point of consideration for those in the CC field. In some sense this represents yet another possible domain where CC stands to make a mark. But there are several things that make this particular domain of peculiar interest.

First, **there is nothing particularly new** about the challenge being posed in this domain. Many CC researchers are currently interested in designing systems that can generate artifacts that would be considered creative in the visual art domain [13]–[15]. So much of the groundwork has already been laid, and we have strong reason to hope that we will to some meaningful extent find success in achieving a solution.

Second, **the impact factor is likely to be significant**. If indeed an arbitrary NP-complete problem can be rendered as a colored graph and then as a KAMI puzzle (as indeed we believe it can be), then an automation of that process to any extent puts real-world, NP-complete problems right under tens of thousands of people's itching, anxious fingertips in a format and on a platform that they already love and are familiar with. Besides the impact of finding solutions to some important real-world problems, the impact of empowering *people* to use their collective intuition and knowledge to solve those problems—particularly in a world where AI is continuously threatening to render such intuition and knowledge obselete—could be equally impactful.

Third, building off of the previous point, **this is an excellent example of practical CC**. One of the challenges that has been hypothesized as being a barrier to growth for the field of CC is its practical applicability [16]. Whereas the world sees great practical value in many of the advances of AI in general, the same has not proven as true for many of the advances of CC. The more we can demonstrate the practical value of CC to society, the more we will see greater growth and success as a community.

Fourth, **KAMI is only one of many domains/platforms via which CC could be used to render computationally-intractable, real-world, complex problems in accessible mediums.** We might just as easily ask: *Given an arbitrary data structure representing an arbitrary NP-complete problem, what is the most creative (i.e., novel, valuable, surprising, intentional) musical/literary/culinary/visual art puzzle that can be used to represent that structure?* More than simply representing an isolated example of applied CC, we are suggesting a possible paradigm shift in motivation. Constraints lie at the heart of so many of the forms of creativity we seek to emulate in our CC systems. Rather than learning these constraints purely from a database of existing artifacts or arbitrarily defining them ourselves, could we not literally derive these constraints via some algorithmic reduction from the constraints we face in real-world problems of interest?

IV. Challenges and Solutions

As we consider the steps necessary to reduce a real-world NP-complete problem to a colored graph, an immediate challenge that surfaces is: What if the reduction results in a colored graph that is too large, complex, or convoluted to be capable of being rendered as a KAMI puzzle that anyone would want to solve? There will almost surely be real-world problems for which this will be the case. But we might draw some hope from recalling the No Free Lunch Theorems for Optimization [17] which put forth that "for any algorithm, any elevated performance over one class of problems is offset by performance over another class." We might reasonably hope to find real-world classes of problems for which the reduction proves effective.

An equally valid challenge to the hypothesis we have presented would be to argue that even NP-complete problem instances of small sizes can be solved via brute-force algorithms in relatively short order. Given the limited canvas size of a KAMI puzzle, one might reasonably conjecture that any NP-complete problem that could be reduced to a puzzle that size would be trivial to solve in its original form by a brute force algorithm. Such may well be true. However, even with a canvas of the sizes shown in the figures above, the complexity of the underlying graphs grows exponentially with the size of the canvas, suggesting that non-trivial problem instances ought to be capable of being represented as KAMI puzzles.

In considering these and other challenges, there may be other ways to make even more complex puzzles accessible to the power of "human computing". For example, what if rather than expecting a puzzle to be solved by individuals, the puzzle is framed as a team-based competition? What if individuals are partitioned subsections of the puzzle to be solved, with optimal sub-solutions being combined in creative ways (e.g., via dynamic programming or divide-and-conquer algorithms)?

As stated in the introduction, as an initial exploration into the domain, our purpose has been primarily to create a blueprint for a future research agenda that will undoubtedly reveal a host of challenges not yet considered. But we hope that the work undertaken thus far will suffice to facilitate meaningful conversation with the community, conversation that may yield additional insights, solutions, and collaborations as we take next steps. In some sense, we rely on the research community itself to be its own crowdsourcing platform.

We have presented the hypothesis that arbitrary NP-complete problems can be reduced to a KAMI puzzle. The KAMI platform, with its tens of thousands of users, represents an ideal means by which to crowdsource solutions to optimization and decision problems of real-world significance. The success of the KAMI platform in this endeavor depends on the effective application of CC principles to render the underlying problem as a puzzle whose creativity will be sufficiently engaging so as to entice the masses to seek its solution. As such it represents a practical and impactful application of CC. In a broader sense, the approach suggests a possible paradigm shift towards using CC in general to represent complex real-world problems in more accessible ways to large groups of people for the purposes of leveraging "human computing" power. We eagerly look forward to advancing the research agenda we have laid out and to addressing the challenges that will arise in the process.

REFERENCES

[1] C. A. Shaffer, V. Karavirta, A. Korhonen, and T. L. Naps, "Opendsa: beginning a community active-ebook project," in *Proceedings of the 11th Koli Calling International Conference on Computing Education Research*, 2011, pp. 112–117.

[2] R. M. Karp, "Reducibility among combinatorial problems," in *Complexity of computer computations*. Springer, 1972, pp. 85–103.

[3] J. D. Ullman, "NP-complete scheduling problems," *Journal of Computer and System Sciences*, vol. 10, no. 3, pp. 384–393, 1975.

[4] P. M. Bodily, M. S. Fujimoto, Q. Snell, D. Ventura, and M. J. Clement, "Scaffoldscaffolder: solving contig orientation via bidirected to directed graph reduction," *Bioinformatics*, vol. 32, no. 1, pp. 17–24, 2016.

[5] J. Weinman, "Cloud computing is NP-complete," in *Proc. Tech. Symp. ITU Telecom World*, 2011, pp. 75–81.

[6] A. Ismaili, T. Yamaguchi, and M. Yokoo, "Student-project-resource allocation: Complexity of the symmetric case," in *International Conference on Principles and Practice of Multi-Agent Systems*. Springer, 2018, pp. 226–241.

[7] M. Parandehgheibi and E. Modiano, "Robustness of interdependent networks: The case of communication networks and the power grid," in *2013 IEEE Global Communications Conference (GLOBECOM)*. IEEE, 2013, pp. 2164–2169.

[8] L. Zambito, "The traveling salesman problem: a comprehensive survey," *Project for CSE*, vol. 4080, 2006.

[9] R. Clifford, M. Jalsenius, A. Montanaro, and B. Sach, "The complexity of flood filling games," *Theory of Computing Systems*, vol. 50, no. 1, pp. 72–92, 2012.

[10] S. Cooper, F. Khatib, A. Treuille, J. Barbero, J. Lee, M. Beenen, A. Leaver-Fay, D. Baker, Z. Popović *et al.*, "Predicting protein structures with a multiplayer online game," *Nature*, vol. 466, no. 7307, pp. 756–760, 2010.

[11] J. H. M. Jensen, M. Gajdacz, S. Z. Ahmed, J. H. Czarkowski, C. Weidner, J. Rafner, J. J. Sørensen, K. Mølmer, and J. F. Sherson, "Crowdsourcing human common sense for quantum control," *Physical Review Research*, vol. 3, no. 1, p. 013057, 2021.

[12] A. Kulkarni, "The complexity of crowdsourcing: Theoretical problems in human computation," in *CHI Workshop on Crowdsourcing and Human Computation*, 2011.

[13] D. Heath and D. Ventura, "Before a computer can draw, it must first learn to see," in *Proceedings of the 7th International Conference on Computational Creativity*. Citeseer, 2016, pp. 172–179.

[14] S. Colton, "The painting fool: Stories from building an automated painter," in *Computers and Creativity*. Springer, 2012, pp. 3–38.

[15] J. Correia, P. Machado, J. Romero, and A. Carballal, "Evolving figurative images using expression-based evolutionary art." in *Proceedings of the 3rd International Conference on Computational Creativity*, 2013, pp. 24–31.

[16] P. Bodily and D. Ventura, "What happens when a computer joins the group?" in *Proceedings of the 11th International Conference on Computational Creativity*, 2020.

[17] D. H. Wolpert and W. G. Macready, "No free lunch theorems for optimization," *IEEE Transactions on Evolutionary Computation*, vol. 1, no. 1, pp. 67–82, 1997.