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Use Of Jigsaw Puzzle Solving Algorithms In The Real World

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Abstract

This paper examines the Jigsaw puzzle problem, which has already been extensively studied in the literature. Several algorithms with efficient time complexity have been developed specifically for “digital” jigsaw puzzles. However, the counterpart: the “real world” jigsaw puzzle, has received relatively little attention in the literature. While some small-scale projects have addressed this issue, we were unable to find any papers discussing it.

The puzzle problem can be divided into two separate components: the “Comparator” whose objective is to determine whether two sides of two pieces fit together, and the “Solver” whose objective is to use the information provided by the comparator to find the best way to fit some pieces together.

Solving the problem in the real world has proven to be more challenging compared to the digital realm. This is because all measurements in the real world are noisier than those in the digital world, making it challenging to obtain accurate data from the Comparator. The Solver poses its own set of challenges, as it is an example of a multi-objective optimization problem. Specifically, one objective is to have the fastest algorithm possible, while the other objective is to create an algorithm that performs well with imprecise data. The latter objective is particularly important when solving real-world puzzles.

In the first half of this paper, we developed a Comparator, and evaluate it’s accuracy. We then use the data to demonstrate its incompatibility with the current state-of-the-art algorithm. At this juncture, two options remain to solve the problem: either create a superior Comparator or design a Solver that can operate with noisier data.

The most promising approach to improve the Comparator involves utilizing machine learning, but this requires a substantial amount of data. Conversely, creating a better Solver is a less straightforward task. However, if successful, it could potentially serve as a labeling tool to generate the dataset needed to train a superior Comparator.

The second part of this paper focuses on developing a new Solver algorithm specifically designed to work with noisy data. While the Solver created may not be considered state-of-the-art, as its time complexity ultimately ends up being worse than the current best algorithms, it could still play a fundamental role in solving the problem. As mentioned earlier, it could be employed to solve many small-sized puzzles and use the results to train a better Comparator.

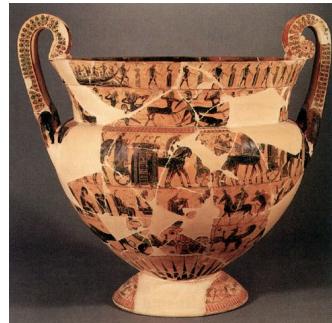
In conclusion, this paper outlines the additional challenges that the real-world puzzle problem presents compared to its digital counterpart. Additionally, it lays the groundwork for a superior machine learning-based Comparator.

1 Introduction

It is fair to say that we are all familiar with jigsaw puzzles. Understanding the “rules” necessary to solve a puzzle is extremely easy, but actually solving large-sized puzzles is not an easy task, neither for humans nor for computers.

While the problem may appear to be a futile style exercise, it could have concrete applications in the future. For instance, it could be applied to the reconstruction of archaeological finds, such as a terracotta pot of [fig. 1](#).

Figure 1: A practical application of a jigsaw puzzle



1.1 Context

This section will provide some basic knowledge related to the jigsaw problem that will be useful for the next sections.

1.1.1 Classification

Puzzles are categorized in different types, for example:

- Type 1 puzzles have the orientation of the pieces known, but the position unknown.
- Type 2 puzzles have both the orientation and the position of the pieces unknown.
- Type 3 puzzles have the orientation of the pieces unknown, but the position known.

Between these categories type 2 are the hardest, and will be the focus of this paper.

1.1.2 Digital vs Real-World Jigsaw Puzzles

There is another important distinction between different types of puzzles. They can be divided into “digital” e.g. [fig. 2](#) and “real world” e.g. [fig. 3](#) jigsaw puzzles. The difference between the two is quite self explanatory, and can be observed in the respective pictures.

Figure 2: An example of a “digital” jigsaw puzzle

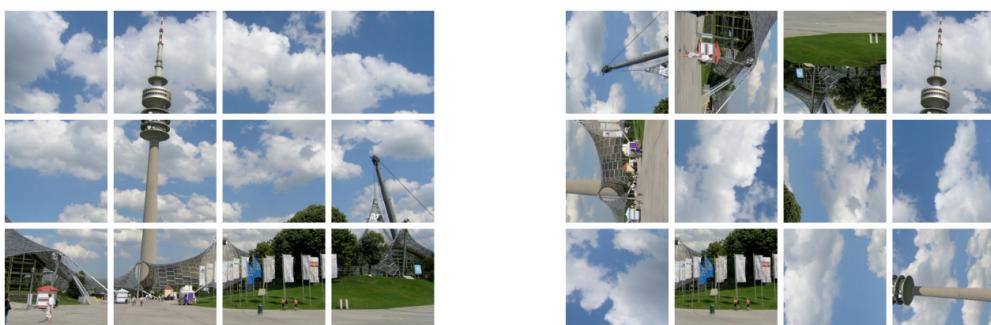
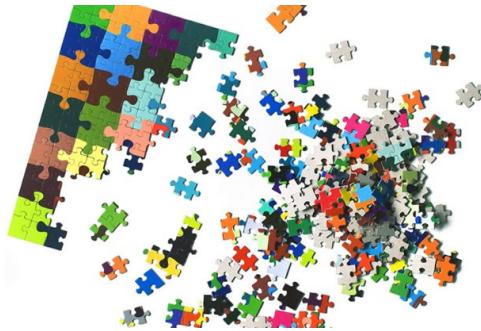


Figure 3: An example of a “real world” jigsaw puzzle



The reason this distinction is important is because, despite the generic concept of the puzzle not changing, obtaining accurate measures of a piece’s characteristics is far easier with a digital puzzle, since there are far fewer things that can go wrong. For example, a piece’s shape may be distorted by a low-quality cut, as seen in [fig. 4](#)

Figure 4: An example of what can go wrong when dealing with the real world



1.2 General Structure Of The Algorithms

A puzzle solver program can be divided into 3 sub algorithms, The Splitter, The Comparator and The Solver. This generalization can be applied not only to our solution, but also to all the algorithms analyzed in the related work section of this paper ([section 3](#)).

1.2.1 The Splitter:

This component takes as input one or more images containing all the pieces. It then separates all the pieces from each other, and split each piece into his four sides.

1.2.2 The Comparator:

This component compares each side with all the others, in order to understand whether they match or not.

There are two distinct kinds of “Comparator” algorithms: The “Binary Comparison” and the “Non Binary Comparison”. As the name suggests when comparing two sides with a “Binary Comparison” the result can either be 0 (they do not match) or 1 (they match). In contrast a “Non Binary Comparison” can give any value between 0 and 1. This allows states of uncertainty to be represented.

1.2.3 The Solver:

This component utilizes the information provided by the Comparator, and attempts to find a solution (i.e. a position and an orientation for each piece) that is the most likely to be correct.

1.3 The Objective Of This Paper

This paper is not the first to tackle the jigsaw puzzle problem in computer science, in fact there have been several more that are mentioned in the related work section ([section 3](#)).

All the papers we read focused on digital jigsaw puzzles exclusively, and we couldn't find any paper that mentioned real-world puzzles. It should be mentioned that we did find some open source project that solved the real-world puzzle problem, but they didn't document the creation process nor the findings given that they weren't trying to write a paper.

This paper's objective is to focus on both digital and real-world jigsaw puzzles, and document why the real-world version is harder, and try to quantify by how much. In order to achieve this objective we want to answer these two questions:

- **What is the difference in execution time between digital and real-world puzzles?**

To answer this question we decided to build a puzzle solver from the ground up, and measure its performance across a set of digital, and real-world puzzles. Our focus when developing this component wasn't to build a state of the art algorithm, as there has already been extensive research put into that; We simply needed something that could work with both digital and real-world puzzles.

- **What are the challenges to use the current state of the art algorithms developed for digital puzzles in the real-world, and how can we overcome them?**

Answering this question is a bit trickier, as an algorithm is divided into Comparator [section 1.2.2](#) and Solver [section 1.2.3](#). Due to the intrinsic difference of digital and real-world jigsaw puzzles reusing the Comparator is impossible, but there is the possibility to reuse the Solver, assuming we could build a Comparator for real-world puzzles that is in the same realm of accuracy achieved by Comparators for digital puzzles. So another way to write this question is: "Can we build a Comparator for real-world puzzles that is accurate enough to work with current state-of-the-art digital puzzle Solvers?"

To answer this question we will measure the accuracy of the comparator we developed and observe what would happen if that accuracy is applied to a digital puzzle Solver. We will then propose a solution to improve the accuracy of real-world Comparators.

1.4 The Dataset

The last step of the introduction is defining our testing dataset. We need both digital and real world puzzles to solve. The dataset used, as well as the code, can be seen in the public GitHub repository: <https://github.com/lucaSartore/PuzzleSolver>.

1.4.1 The Real-World Puzzle

The first step involves selecting a real-world puzzle to solve. It has been decided to utilize a classic 1000-piece puzzle measuring 66cm x 50cm. A printer's scanner is employed to digitize the individual pieces.

The puzzle has been scanned in various sub-sizes to facilitate the testing of different configurations. A resolution of 1200 pixels per inch (ppi) has been employed to ensure a sharp and precise depiction of the pieces, as seen in [fig. 4](#). The puzzle has been scanned backward, using a black background.

This choice has been dictated by the fact that the scanner used has the flashlight slightly off-centered from the scanner's sensor. And this causes shadows to be cast on one side of the pieces. A black background has been chosen to solve the problem of the shadow. And then the pieces have been flipped backward, since many of them were black, and it was difficult to separate them from the background. In the future it would be possible to scan the pieces in the correct orientation, by using a different scanner.

1.4.2 The Digital Puzzle

The digital puzzles have been obtained from <https://puzzle.telegnom.org/>. This web app can generate a puzzle from a dimension and a jitter value. The jitter is a parameter that controls how unique and distorted the puzzle images are, see [fig. 9](#). The default jitter used in the tests is 5%.

2 Our Implementation Of A Puzzle Solver

This section will describe the implementation of the puzzle solver we developed. This solver will then be put to the test in the next sections.

2.1 Our Splitter

2.1.1 Splitting The Pieces

As introduced in [section 1.2.1](#), the initial stage in puzzle solving involves splitting an image composed of many pieces into individual ones. This is relatively straightforward, and can be done with the following steps:

- Apply a threshold and transform an RGB image into a binary mask.
- Find all individual Blobs (a Blob is defined as a set of connected pixels with the same color) and for each one:
 - Calculate the area (the number of pixels the Blob is made of)
 - Add it to the set of pieces only if his area in within a certain range (to avoid small pieces of dust ending up counted as pieces)

2.1.2 Splitting The Sides

The next step following the general structure described in [section 1.2.1](#) is to split a piece into his 4 sides, this can be done with the following steps:

- **Remove the holes from the piece:**

To remove the holes from the piece, the program employs a three-step process. Initially it computes the convex hull of the piece [fig. 5b](#). Subsequently it calculates the difference between the convex hull and the original image, resulting in an “image with filler areas” [fig. 5c](#). It can be noted that these filler areas have distinct shapes, depending on what has generated them (either a “hole” or a “knob”). Therefore they can be categorized. Finally the filler areas are added back to the original only if they originated from a hole. This results in an image where the holes have been filled [fig. 5d](#)

- **Remove the knobs from the piece:**

In order to remove the knobs from the piece, the image without holes undergoes an erosion [fig. 5e](#) followed by a dilation [fig. 5f](#). This process results in an image that resembles the original, but without any knobs. Subsequently, the program identifies the pixels that are white in the image without holes [fig. 5d](#), but not in the eroded and dilated version [fig. 5f](#). This leads to the formation of a set of blobs [fig. 5g](#). It is important to note that the shape of a blob can vary significantly depending on whether it originated from an “angle” or a “knob” and thus they can be classified accordingly. Following this, the program proceeds to eliminate from the hole-free image [fig. 5d](#) all pixels that are in close proximity to a blob generated by a knob. This operation yields an image that is both devoid of knobs and holes [fig. 5h](#).

- **Find the coordinates of the four corners:**

In order to determine the coordinates of the corners, the program employs a three-step approximation method. Initially, it identifies the minimum enclosing rectangle and utilizes the

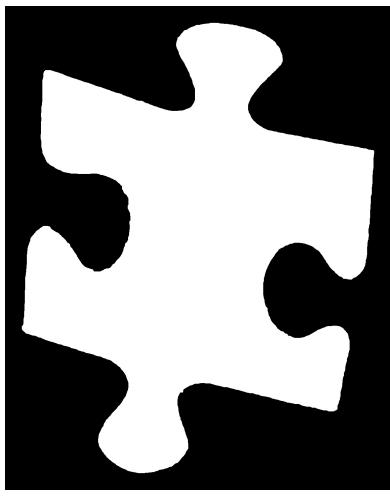
coordinates of its corners as the first approximation [fig. 5i](#).

For the second approximation, the program selects, from the white pixels in close proximity to the first approximation, the pixel that contains the highest number of black pixels within a specified range. Then it considers only the pixels that are within a certain distance of the second approximation, and finds the minimum enclosing triangle of sed pixels [fig. 5j](#).

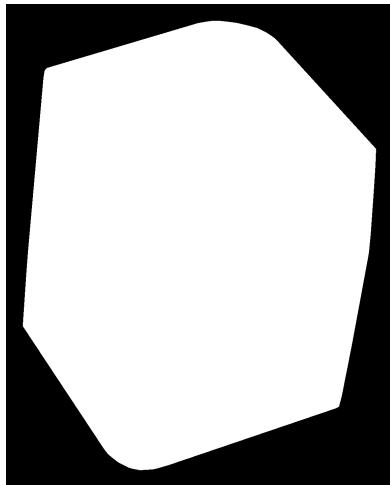
The corner of the triangle that is nearest to the second approximation serves as the third and final approximation for the corner of the puzzle piece. The position of the four corners can be seen in image [fig. 5k](#).

- **Split each piece into four sides using the previously found coordinates:**

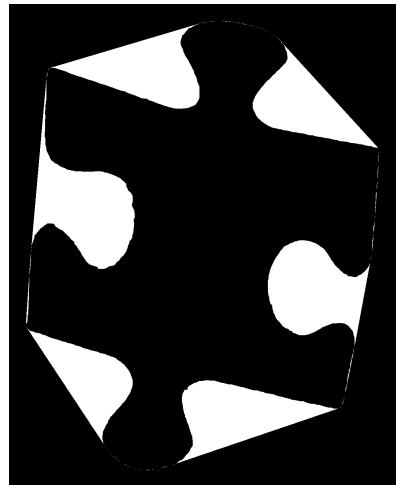
After the program has successfully identified the four corner coordinates, it can straightforwardly derive each of the four sides. An example of a single side can be seen in image . [fig. 5l](#).



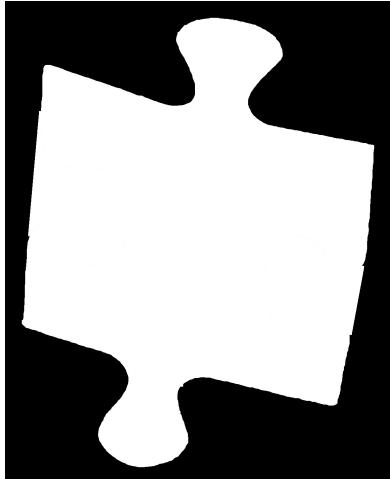
(a) Original binary mask of a piece.



(b) Convex Hull of a piece.



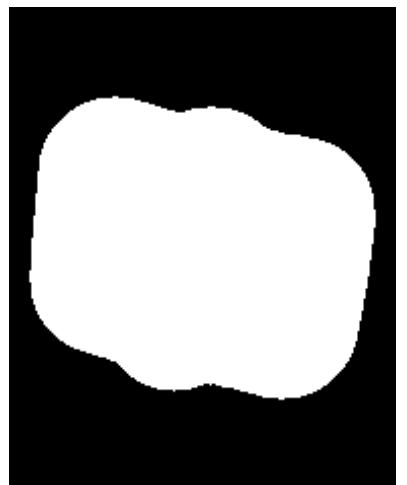
(c) Difference: [fig. 5b](#) – [fig. 5a](#).



(d) Piece [fig. 5a](#) with holes removed.



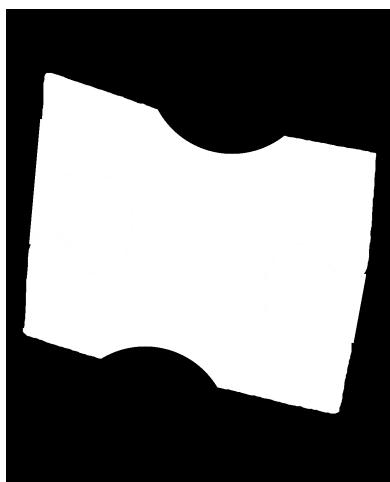
(e) Mask [fig. 5d](#) eroded.



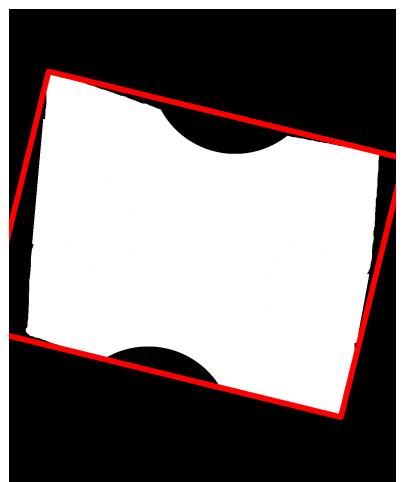
(f) Mask [fig. 5e](#) dilated.



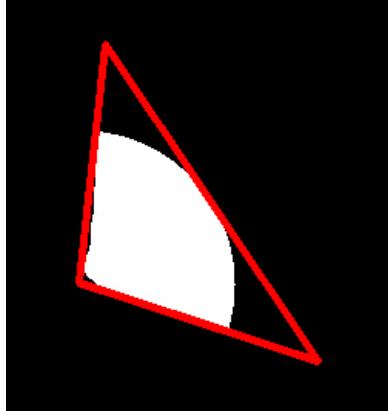
(g) Difference: [fig. 5d](#) – [fig. 5f](#).



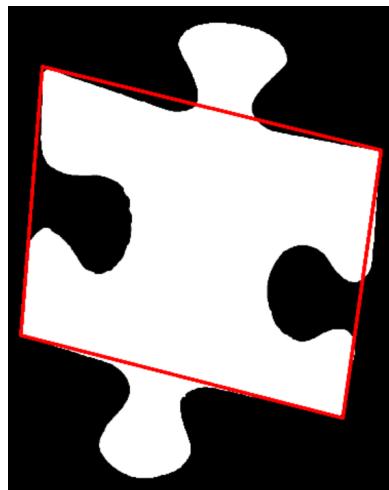
(h) Piece [fig. 5d](#) with knobs removed.



(i) Min enclosing rectangle of [fig. 5h](#).



(j) Min enclosing triangle of the bottom right corner of fig. 5h.



(k) The corners of the piece fig. 5a.



(l) One of the sides of the piece fig. 5a.

Figure 5: Steps needed to split an image into his four sides.

2.2 Our Comparator

The next step is to compare the sides that have been generated before, in order to generate a compatibility shore. To achieve this, the program employs the following steps:

- For each side, it considers only the border, and makes it thicker.
- It puts two sides attached to each other using the coordinates of the corners (In the same way a human would do to test if two pieces fit together).
- It calculates the “Or Area”; that is, the number of pixels that belong to the border of one side or the other.
- It calculates the “And Area”; that is, the number of pixels that belong to the border of both sides.
- It calculates the final shore, which is defined as: $Shore = \frac{AndArea}{OrArea}$, and goes from 0 to 1.

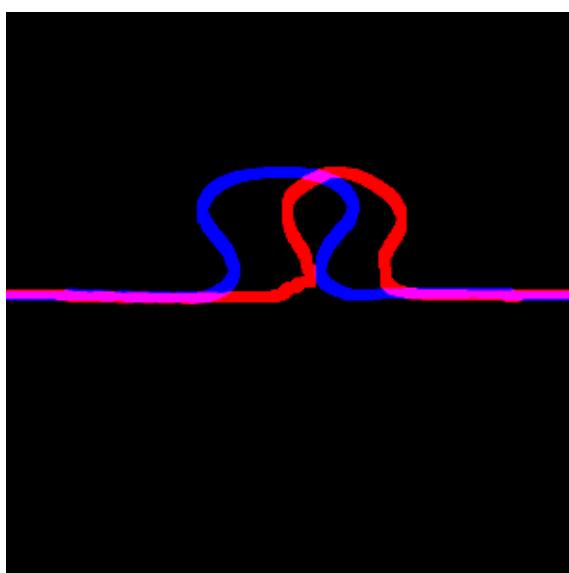


Figure 6:

In this image we can see two sides that have been compared, one side is drowned in red, the other one in blue. In this picture, the “Or Area” is represented by all non black pixels; The “And Area” is represented by all the purple pixels.

2.3 Our Solver

The Solver we developed cannot be considered state-of-the-art when compared to the current best digital puzzle solvers. However, it may be considered as such when compared to existing “real-world” puzzle solvers.

Regardless, the achieved performances are still good enough to test and understand the differences between digital and real-world puzzles, which is the main objective of this paper.

2.3.1 Overview

The algorithm itself is relatively straightforward. It operates as a recursive procedure, initiating by recognizing all 2x2 sets of matching pieces through the combination of four individual pieces. Subsequently, it extends this process to identify all 4x4 sets of matching pieces by aggregating four 2x2 pieces, and this pattern continues recursively.

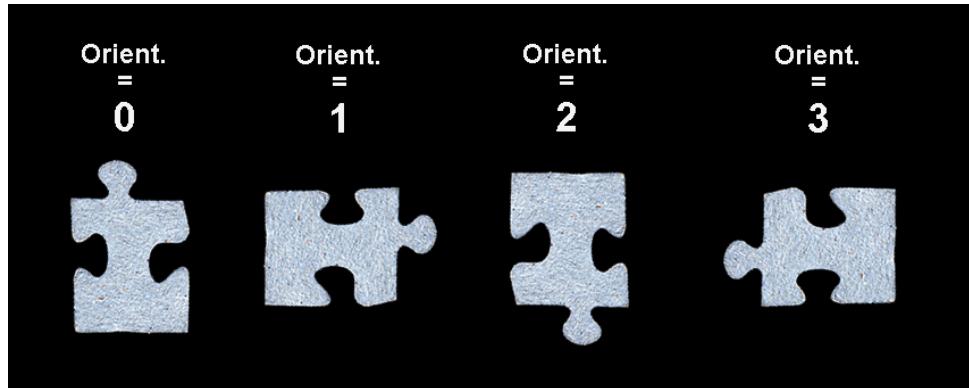
2.3.2 Basic Components

To implement the algorithm two fundamental object are defined

- **SinglePiece**: which contains information about a single puzzle piece.
- **PPieceGroup<T>** where T can be either a **PieceGroup** or a **SinglePiece**
This element encompasses four elements of type T, each with its own position (top right, top left, bottom left, bottom right).

Both **SinglePiece** and **PieceGroup** have an “orientation” attribute that goes from 0 to 3, this attribute represent the orientation of the piece, as shown in [fig. 7](#).

Figure 7: orientation attribute of an object



2.3.3 The Levels

These objects are assigned levels:

- **SinglePiece** is at level 0, representing a 1x1 “solution” to a puzzle.
- **PieceGroup<SinglePiece>** is at level 1, representing a 2x2 solution to a puzzle.
- **PieceGroup<PieceGroup<SinglePiece>>** is at level 2, representing a 4x4 solution to a puzzle, and so forth.

2.3.4 The Behaviors

These basic objects also have the following shared behaviors:

- 4 objects of level N can be combined to build an object of level N+1.

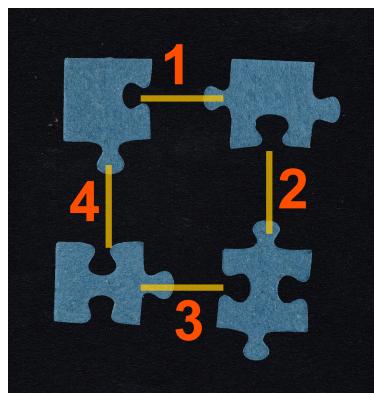
- One object of level N has 4 sides, each of which can be compared with a side of an element of level N. This results in a compatibility shore.
 - The comparing shore for level 0 objects is just the shore given by the Comparator of [Section 1.2.2](#).
 - The comparing shore for level N+1 objects is the average between two comparisons made with objects of level N

2.3.5 Combining four objects

When combining four objects into one, some comparisons are executed to ensure that the resulting piece is a valid combination.

- The right side of the object in the top left position is compared with the left side of the object in the top right position [fig. 8\(1\)](#).
- The bottom side of the object in the top right position is compared with the top side of the object in the bottom right position [fig. 8\(2\)](#).
- The left side of the object in the bottom right position is compared with the right side of the object in the bottom left position [fig. 8\(3\)](#).
- The top side of the object in the bottom left position is compared with the bottom side of the object in the top left position [fig. 8\(4\)](#).

Figure 8: Example of a combination of four objects in to one



In order for the created object to be considered valid all of the comparisons must have a shore greater than the constant `MIN_SHORE_SINGLE_SIDE`. And the average of the four comparisons must be greater than the constant `MIN_SHORE_PIECE_GROUP`.

The process also checks that all individual pieces inside a newly created object are different (because obviously is impossible to reuse the same piece twice to solve a puzzle)

2.3.6 The Algorithm

As mentioned earlier, the algorithm is implemented with a recursive function. The function is generic, and can take as input objects of any level.

A Function of level N takes as input a list of objects of level N, and creates all possible objects with level N+1. Then it uses the newly created objects to generate a recursive call on a version of itself with level N+1. This process is repeated until the desired size is reached.

```

# This function returns a list of object that match with 'piece_to_match'
# along the direction 'direction'.
# It also filters the data to return only pieces with an index greater than 'index_filter'
# This function is executed in constant time, since it relies on some pre-processing of
# the data
def get_matches(piece_to_match, direction, index_filter):
    ...

def solve<T>(pieces: List<T>):

    number_of_pieces = pieces.length()

    found_pieces = List::<PieceGroup<T>>::new()

    # this function compare all pieces with the others, and build some data structures
    # that are used from the function 'get_matches'
    # the time complexity is o(N^2)
    do_pre_processing(pieces)

    # test all possible combinations for the top left piece
    for top_left_index in 0..number_of_pieces:
        for top_left_orientation in 0..4:

            # get the top left piece
            top_left = get_piece(top_left_index, top_left_orientation)

            # test all possible combinations of top_right, bottom_right and bottom_left
            for top_right in get_matches(top_left, RIGHT, top_left_index):
                for bottom_right in get_matches(top_right, DOWN, top_left_index):
                    for bottom_left in get_matches(bottom_right, LEFT, top_left_index):

                        # try to create the new piece group
                        new_element = PieceGroup::new(top_left, top_right,
                            bottom_right, bottom_left)

                        if new_element.is_valid():
                            # if the 4 pieces can fit together the newly created piece
                            # is added to the list of found pieces
                            found_pieces.add_element(new_element)
                        else:
                            # otherwise the program check what the case of the
                            # invalid creation is, and generate a continue
                            # on the respective loop, to speed up the operations
                            continue_failure_cause_loop()

    # at the end a recursive call is generated
    return solve::<PieceGroup<T>>(found_pieces)

```

The procedure begins by testing all possible pieces and orientations as the top_right piece. Then continues by finding all the other 3 pieces in an efficient way thanks to get_matches. When the program has an hypothesis on the 4 pieces that can build a new piece it tries to create it.

The creation process does some checks, and if everything is successful it adds the piece to the list of found pieces. If the creation is not successful it figures out which piece has caused the failure, and moves to the next iteration of the respective loop.

When all combinations have been found, the function makes a recursive call and the process is repeated.

The process ensures that the piece in the top_left is always the one with the lower index. This is done to avoid building the same piece 4 times with 4 different orientations.

One advantage of this algorithm is that the outer edge for loop can be easily parallelized to achieve

better performances.

It should be noted that this pseudo code omits many details, two of which are:

- A condition that checks if the desired size has been reached and eventually stops the recursion.
- A condition that specifically handles cases where the final size of the puzzle can't be reached simply by combining 4 pieces together recursively. Without this condition the algorithm could only solve squared puzzles. Who's size is a power of 2.

3 Related work

Now that we have developed our own solution, it would be interesting to see how it compares against the current state-of-the-art algorithms for both digital and real-world jigsaw puzzles. This section gives a brief introduction to 3 state-of-the-art algorithms, so that they can be compared with our solution in the conclusions.

3.1 Solving Jigsaw Puzzles By The Graph Connection Laplacian [1]

This algorithm falls within the “binary comparison” category ([section 1.2.2](#)). And can be used to understand the strength and weaknesses of this approach.

The primary advantage of this approach lies in its speed; the utilization of binary comparison permits specific optimizations, particularly leveraging graph theory techniques.

The algorithm exhibits a time complexity of approximately $O(N^2)$, a value consistent with the theoretical minimum for jigsaw puzzle solving, as outlined in the study “No easy puzzles: Hardness results for jigsaw puzzles [3]”.

However, a potential drawback may arise in terms of accuracy. This stems from the fact that, with only two states (matching or not matching), certain details may be lost when compared to a non-binary comparison. To quantify accuracy the paper used the “neighbors comparison” metric, which “calculates the percentage of pairs of image patches that are matched correctly”. This will be useful later.

3.2 A Genetic Algorithm-Based Solver for Very Large Jigsaw Puzzles [2]

This paper employs genetic algorithms to address the jigsaw puzzle problem, yielding promising results. The algorithm seems to have a $O(N^2)$ time complexity, with execution time slightly lower than the previous example (However, it remains uncertain which one is faster, as the papers did not specify the particular hardware configuration used).

The paper adopts the same evaluation method for accuracy as the previous example, namely neighbor comparison, facilitating direct comparison between the two approaches. This algorithm falls under the category of “Non binary comparison” [section 1.2.2](#) a distinction that theoretically grants it an advantage due to the increased granularity of input data. Unfortunately this advantage does not compensate for the worst precision of the algorithm itself, and the accuracy results are equivalent, if not slightly worse than the previous algorithm.

It is important to keep in mind that for the very nature of genetic algorithms, it might be possible that the accuracy would have been better if they had allowed the algorithm to run for more generations.

3.3 Computer Vision Powers Automatic Jigsaw Puzzle Solver [4]

Solutions [section 3.1](#) and [section 3.2](#) can be considered “state-of-the-art” for digital jigsaw puzzles. However, as already introduced in section [section 1.1.2](#), translating these solutions to the real world can be challenging.

This article represents one of the most comprehensive and well-documented implementations for real-world puzzles. However, it’s important to note that referring to this approach as a “solution” may be misleading, as it primarily identifies the top eight matching pieces for a specific point and subsequently

relies on user input to make the final placement decision. This aspect renders the algorithm non-autonomous..

Even disregarding this significant detail, conducting an analysis of this solution has proven to be challenging, as the article leans more towards a publicity stunt than an academic paper. In fact, the code is not open source, and informations regarding the time needed to solve the puzzle are absent. The article only showcases a single puzzle solved, with dimensions of 9×6 .

Despite these limitations, this article still stands as one of the best examples of a solution for real-world puzzles.

4 Evaluation

This section will evaluate the proposed solution by measuring two key metrics: execution time and accuracy. The objective of this section is to answer the first question posed in [section 1.3](#):

- What is the difference in execution time between digital and real-world puzzles?

4.1 Execution Time Analysis

This section measures the execution time of many puzzles, and shows the results. The puzzles that has been used for this test has been described in [section 1.4](#).

The constants `MIN_SHORE_SINGLE_SIDE` and `MIN_SHORE_PIECE_GROUP` mentioned in section [section 2.3.5](#) were set at different values depending on the nature of the puzzle (real or digital).

The test has been performed on a ryzen 5 5600 CPU with 16 GB of RAM. The time measured in the test does not include the execution time of the Comparator [section 2.2](#), but only the one of the Solver [section 2.3](#).

4.1.1 Digital vs Real World Puzzles

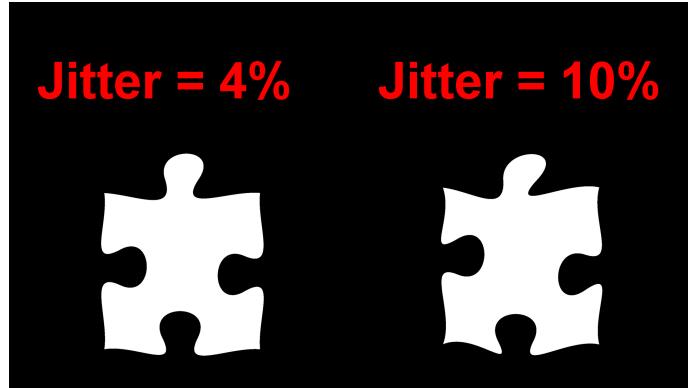
In the table below we can see how the same algorithm can have vastly different performance depending on the kind of puzzle it is working with.

Size	Pieces	Execution time [s]	
		Digital puzzle	Real Puzzle
2x3	6	1	4
3x4	12	3	14
4x4	16	4	59
4x5	20	4	48
5x8	40	20	627
8x8	64	30	2851
8x12	96	660	N/A
16x16	256	377	N/A

Looking at the data we can spot two anomalies:

- The 4x5 real puzzle has a lower execution time than the 4x4 real puzzle. This is not a big difference and can be attributed to run to run variation.
- The 8x12 digital puzzle has a much higher execution time than the 16x16 digital puzzle. This is also easily explainable, as puzzles whose side is not a power of two are in general harder compared to those who fulfill this condition. As they require an extra step compared to the simple algorithm shown in [section 2.3](#).

Figure 9: Effect of jitter on jigsaw pieces



4.1.2 Effect of Jitter on Execution Time

As mentioned in [section 1.4](#) the digital puzzle have an attribute called jitter. Intuitively increasing the jitter would make the pieces harder to match with each other, and consequently making the puzzle easier to solve. And we can observe that this intuition is correct in the table below.

Jitter effect on an 8x8 digital puzzle	
Jitter	Execution time [s]
4%	104
5%	30
6%	17
8%	17
10%	16

This shows how the execution time can be six times faster just by making each piece more unique.

4.1.3 Run to Run Variation

Another feature of the algorithm that is worth testing is his consistency. To measure tested the performance on 5 distinct puzzles, with the only thing in common been a size of 4×4 .

Run to run variance on a 4×4 real puzzle		
Execution time [s]	Average	Standard deviation
64		
68		
43		
24	47.8	18.6
29		
59		

4.1.4 Accuracy

It is crucial to mention that the project currently lacks an automated method for evaluating the accuracy of the results. However, the accuracy of two real-world puzzles (4×4 and 8×8) and one digital puzzle (16×16) has been manually confirmed, with them achieving a 100% correctness.

Manually evaluated accuracy of the solutions		
Puzzle size	Puzzle kind	Accuracy
4×4	real world	100%
8×8	real world	100%
16×16	digital	100%

4.1.5 Answering The Question

This paper has asserted from the beginning that real-world puzzles pose greater challenges compared to their digital counterparts. While some intuitive explanations were provided to support this assertion, a proof hasn't been presented until now. This test ultimately substantiates the claim, demonstrating that the performance of the same algorithm can vary significantly depending on the accuracy of the input data.

5 Conclusion

This sections aim to conclude the paper by answering the second question posed in [section 1.3](#):

- What are the challenges to use the current state of the art algorithms developed for digital puzzles in the real-world, and how can we overcome them?

At the end of the section we will also make some consideration about possible future works related to this problem.

5.1 Applying Already Existing Algorithms To The Real World

Comparing the results achieved by our algorithm with some of the algorithms seen in the related work section ([section 3](#)), clearly shows how our algorithm is far away from the current state-of-the-art digital puzzle solvers. In this section we want to see if it is possible to use our comparator with current state-of-the-art algorithms. In particular we selected the “Graph Connection Laplacian” [1] solution, due to the comprehensive details provided in the paper. Notably, it contains information regarding the algorithm’s accuracy in relation to the corruption rate, which is crucial for this analysis.

Unfortunately the conducted tests reveal that the Comparator we developed in [section 2.2](#) and the “Graph Connection Laplacian” solution of [section 3.1](#) are not compatible with each other. A proof supporting this assertion is presented subsequently.

5.1.1 Selecting The Threshold Based On Input Data

The comparison algorithm described in [section 2.2](#) outputs a compatibility shore that goes from 0 to 1.

But the graph connection Laplacian algorithm of [section 3.1](#) takes as input a binary value. Which means that it is necessary to apply a threshold to the input data to convert them from float to bool.

To find the optimal threshold we solved a small 16 piece puzzle. And we measured the following 4 values in function of the threshold:

- **match%:**

The probability that 2 randomly selected sides matches.

- **correct combination match% (or c.c match%):**

The probability that 2 randomly selected sides matches given that in the correct puzzle solution they are actually close to each other. Ideally this should be 1, as we would prefer that the comparison never returns false if two pieces are actually connected in the correct solution.

- **limit match%:**

Given that this measures has been taken on a 16 piece puzzle, the match% is highly influenced by the correct piece matching together. With a bigger puzzle the match% would be lower (Given that the amount of correct couple of sides scales with N , while the amount of possible couple of sides scales with N^2 . Where N is the number of pieces).

Limit match% is an approximation of what the match% would be in the limit for $N \rightarrow +\infty$. This value is obtained by subtracting to match% the probability of choosing randomly the correct side, multiplied by the probability that the comparison returns true (which is c.c match%).

Ideally limit match% should be almost zero, as we would prefer that the comparison is true only when the pieces are actually connected in the correct solution.

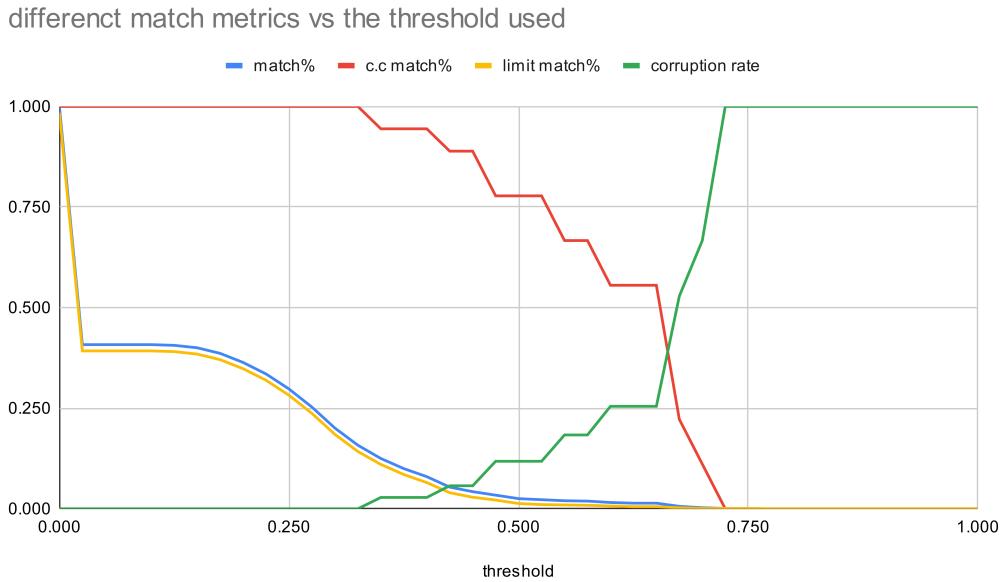
$$limit\ math\% = math\% - \frac{c.c.\ math\%}{16 \times 4}$$

- **corruption rate:**

Is defined as: $1 - \sqrt{c.c\ match\%}$. Ideally this should be 0.

threshold	match%	c.c match%	limit match%	corruption rate
0.000	1.000	1.000	0.984	0.000
0.025	0.408	1.000	0.392	0.000
0.050	0.408	1.000	0.392	0.000
0.075	0.408	1.000	0.392	0.000
0.100	0.408	1.000	0.392	0.000
0.125	0.406	1.000	0.391	0.000
0.150	0.400	1.000	0.385	0.000
0.175	0.386	1.000	0.371	0.000
0.200	0.364	1.000	0.348	0.000
0.225	0.335	1.000	0.319	0.000
0.250	0.298	1.000	0.282	0.000
0.275	0.253	1.000	0.237	0.000
0.300	0.201	1.000	0.185	0.000
0.325	0.158	1.000	0.142	0.000
0.350	0.125	0.944	0.110	0.028
0.375	0.100	0.944	0.085	0.028
0.400	0.080	0.944	0.065	0.028
0.425	0.054	0.889	0.040	0.057
0.450	0.043	0.889	0.029	0.057
0.475	0.034	0.778	0.022	0.118
0.500	0.025	0.778	0.013	0.118
0.525	0.023	0.778	0.010	0.118
0.550	0.020	0.667	0.010	0.184
0.575	0.019	0.667	0.009	0.184
0.600	0.016	0.556	0.007	0.255
0.625	0.014	0.556	0.005	0.255
0.650	0.014	0.556	0.005	0.255
0.675	0.006	0.222	0.003	0.529
0.700	0.003	0.111	0.001	0.667
0.725	0.001	0.000	0.001	1.000
0.750	0.001	0.000	0.001	1.000
0.775	0.000	0.000	0.000	1.000
0.800	0.000	0.000	0.000	1.000
0.825	0.000	0.000	0.000	1.000
0.850	0.000	0.000	0.000	1.000
0.875	0.000	0.000	0.000	1.000
0.900	0.000	0.000	0.000	1.000
0.925	0.000	0.000	0.000	1.000
0.950	0.000	0.000	0.000	1.000
0.975	0.000	0.000	0.000	1.000
1.000	0.000	0.000	0.000	1.000

Figure 10: match metrics vs threshold used



Now, let's consider the graph connection Laplacian algorithm of [section 3.1](#) tasked with solving a 500-piece puzzle using our Comparator of [section 2.2](#). A threshold of 0.425 is chosen; This implies a limit match% of 0.04 and a corruption rate of 0.057. What would this mean in terms of accuracy of the results?

5.1.2 Definitions

This set of definitions are useful to better understand the next section:

- **Connection:**

When two sides of two different pieces are joined they form a connection. A solved puzzle with N pieces, (assuming it is squared) has around $2N$ total connections.

- **Possible Combinations:**

A puzzle with N pieces can be put together in many different ways, (Even if not all of them actually fit together). The total number of possible combinations is $N! \times 4^N$ where $N!$ represent all possible way to combine the pieces in a particular position, and 4^N represents all possible orientations that each piece can have.

- **Possible Correct Combination:**

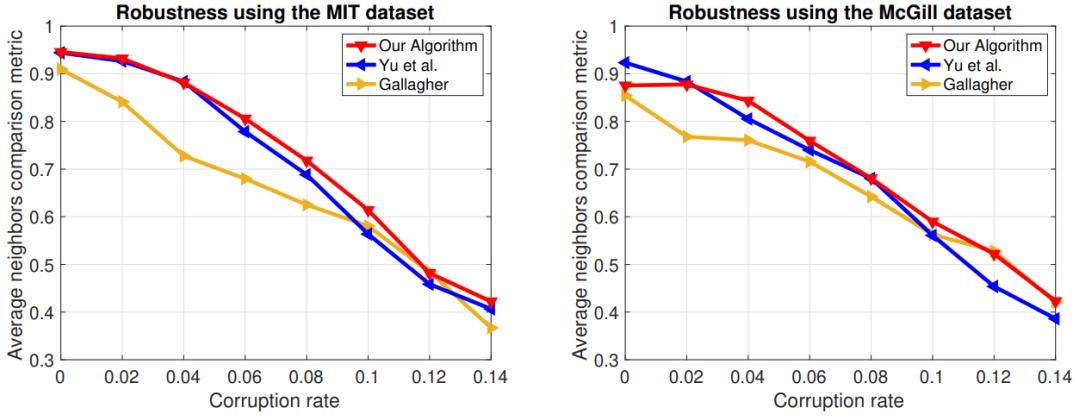
Is one of the possible combinations where all the connections are considered a match by the comparing algorithm.

- **Actual Correct Combination:**

An Actual Correct Combination is a Possible Combination that is also the correct solution of the original puzzle

5.1.3 Corruption Rate Analysis

Figure 11: Neighbors comparison vs Corruption rate of graph connection laplacian algorithm of [section 3.1](#). Image taken from paper [1] page 34.



In [fig. 11](#), it can be observed that at a corruption rate of 0.057, a neighbors comparison metric of roughly 80% can be anticipated. This implies that, on average, one out of every five connections will be incorrect. In the context of a puzzle comprising 500 pieces (equating to approximately 1000 connections), an estimated 200 connections will be inaccurate on average. It is reasonable to assert that this outcome is suboptimal.

5.1.4 Limit Match% Analysis

Let's remember that $limit_match\% = 0.04$.

Given that in a puzzle with N pieces there are around $2N$ connections, the probability of one random combination to be a possible correct combination is: 0.04^{2N} .

The total number of possible combinations are $N! \times 4^N$, which means that on average, in a puzzle with N pieces, there will be $0.04^{2N} \times N! \times 4^N$ possible correct combinations.

For $N = 500$ the expected number of possible combinations is around 1.5×10^{37} . Which makes the chance of finding the actual correct combination basically zero.

5.1.5 Conclusion

In this case both the match% and the corruption rate are bad enough to make a correct reconstruction impossible. To lower limit match% is necessary to increase the threshold, but this would increase the corruption rate. To lower the corruption rate is necessary to decrease the threshold, but this would increase the limit match%. This means that, regardless of the threshold chosen, our comparison algorithm [section 2.2](#) can not work with a state of the art solver [section 3.1](#).

5.2 Future Works

Until now this paper has not painted a positive picture about real-world puzzle solving. The current digital puzzle solver achieves a good time complexity, but requires really precise input data that we didn't manage to achieve with our real-world comparator ([section 2.2](#)). On the other hand we managed to create a Solver ([section 2.3](#)) that could operate with the noisy data generated by our comparator; But the greater reliability came at the expense of time complexity, and this meant that the maximum size of puzzle that could be solved was limited.

Despite this inconvenience we think there is still a chance to solve the problem by significantly improving the comparator.

5.2.1 Machine Learning Based Comparator

Some minor improvements to the comparator can be made by spending some time tweaking the current algorithm. However, it is clear that for a task of this nature, the most viable solution would likely involve leveraging machine-learning techniques.

But this presents a significant challenge: manually testing if certain pieces fit together, followed by scanning and labeling them, is a time-intensive process that could require hundreds, if not thousands, of hours.

However we just created a puzzle solver that, even with a suboptimal time complexity, can easily solve small size real world puzzles. We could use it to solve a couple hundred small size puzzles, and automatically label the results for us, paving the way to a superior machine learning based comparator.

5.2.2 Labeling tool

To facilitate ours or someone else's future attempt to create a machine-learning-based comparator; We added to our program the capability to export the data useful to train a machine learning model. This section will explain the format of the data.

5.2.2.1 Basic notions

One piece is uniquely identified by his id `piece_id`. The id is an integer that goes from 0 to Number of pieces - 1. Each piece has 4 sides that can be identified by the side `side_id`, an integer that goes from 0 to 3.

5.2.2.2 Image of each piece

Inside the folder `results/pieces` the program will generate one image for each one of the pieces of the puzzle. The file will be named `{piece_id}.jpeg`. An example can be seen in [fig. 12](#)

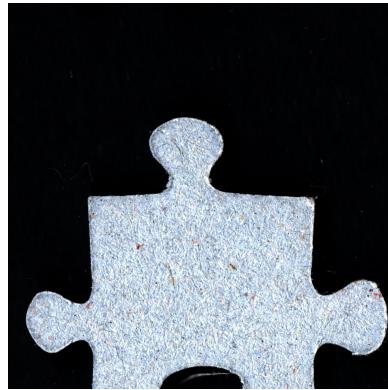
Figure 12



5.2.2.3 Image of each side

Inside the folder `results/sides` the program will generate one image for each side of each piece. The images will be named `{piece_id}-{side_id}.jpeg`. An example can be seen in [fig. 13](#)

Figure 13



5.2.2.4 Corners of each piece

The file `corners.json` will be generated inside the folder `results`. This file will contain a list of pieces. Each piece has 4 sides, and each side has the coordinates of the two points that delimit itself. An example of the generated json can be seen below.

```
[  
  {  
    "piece_id": 0,  
    "side_0": {  
      "p1": {"x":955, "y":1924},  
      "p2": {"x":1024, "y":1016}  
    },  
    "side_1": {  
      "p1": {"x":1024, "y":1016},  
      "p2": {"x":1850, "y":1028}  
    },  
    "side_2": {  
      "p1": {"x":1850, "y":1028},  
      "p2": {"x":1814, "y":1992}  
    },  
    "side_3": {  
      "p1": {"x":1814, "y":1992},  
      "p2": {"x":955, "y":1924}  
    }  
  },  
  {...},  
  {...},  
  ...  
]
```

5.2.2.5 Match for each side

The file `connections_result.json` will be generated inside the folder `results`. This file will contain a list of pieces, each piece has 4 sides, and each side has a link to the side of the piece that matches it. The link can be null if the side is along the border.

An example of the generated json can be seen below.

```
[  
  {  
    "piece_id": 12,  
    "side_0": {  
      "piece": 5,  
      "side": 0  
    },  
    "side_1": {  
      "piece": 8,  
      "side": 0  
    },  
    "side_2": {  
      "piece": 0,  
      "side": 0  
    },  
    "side_3": null  
  },  
  {...},  
  {...},  
  ...  
]
```

5.3 Conclusion

In conclusion, this paper has successfully achieved its objectives. It has provided a comprehensive explanation of why real-world puzzles present greater challenges compared to their digital counterparts. Additionally, it has been shown that the same algorithm can have drastically worse performance when working with real-world puzzles compared to digital ones.

Furthermore, we have developed a highly effective labeling tool, which holds great promise for future applications in creating a machine-learning-based comparator. Such a comparator has the potential to greatly facilitate puzzle-solving algorithms by providing more accurate data.

Even the solver we have created can be considered a success. While its time complexity may be less favorable when compared to state-of-the-art digital puzzle solvers, it stands as a strong contender in the realm of real-world puzzle-solving algorithms. In fact, it may even be considered one of the best available online for tackling real-world puzzles.

All the code used in this project is available on the GitHub repository: <https://github.com/lucaSartore/PuzzleSolver>.

Figure 14: example of a result render of a digital puzzle

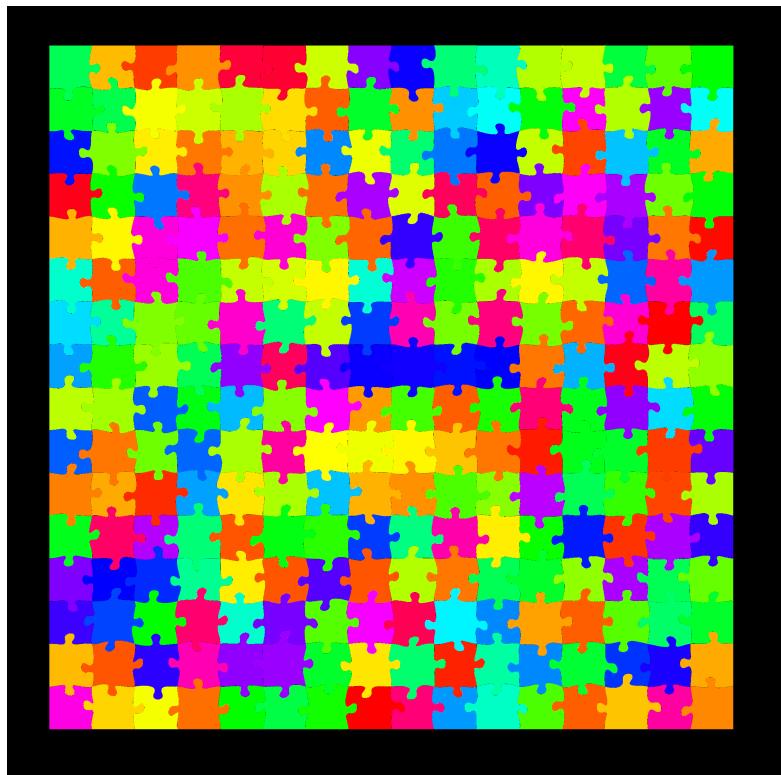
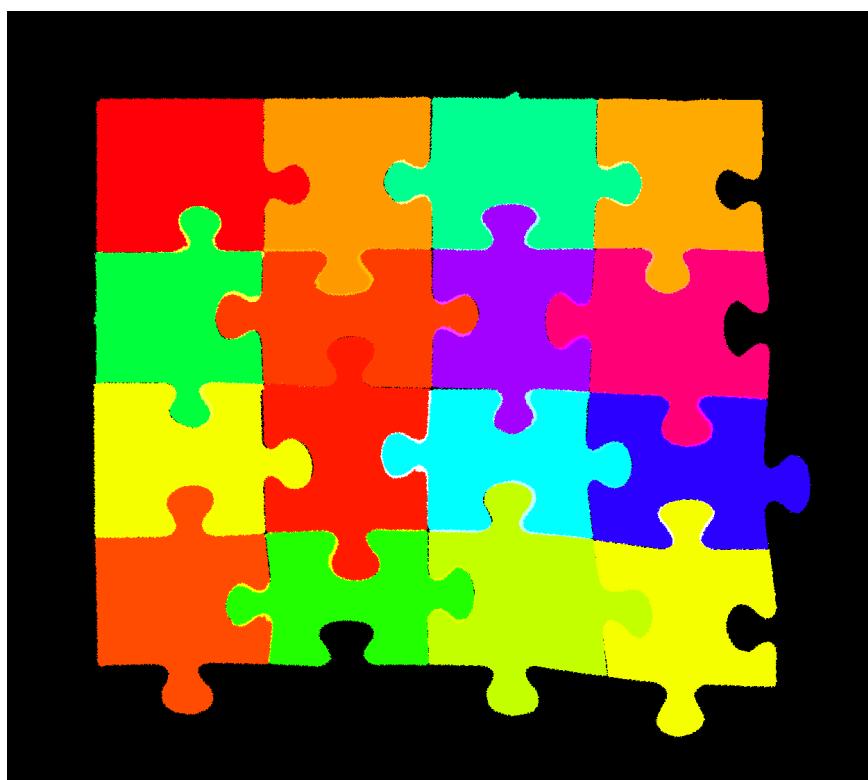


Figure 15: example of a result render of a real world puzzle



References

- [1] Vahan Huroyan, Gilad Lerman and Hau-Tieng Wu, Solving Jigsaw Puzzles By The Graph Connection Laplacian, 2020. <https://arxiv.org/pdf/1811.03188.pdf>.
- [2] Dror Sholomon, Omid David and Nathan S. Netanyahu, A Genetic Algorithm-Based Solver for Very Large Jigsaw Puzzles, 2013. https://openaccess.thecvf.com/content_cvpr_2013/papers/Sholomon_A_Genetic_Algorithm-Based_2013_CVPR_paper.pdf.
- [3] Michael Brand, No easy puzzles: Hardness results for jigsaw puzzles, 2015. <https://www.sciencedirect.com/science/article/pii/S0304397515001607>.
- [4] AbtoSoftware, Computer Vision Powers Automatic Jigsaw Puzzle Solver, 2019. <https://www.abtosoftware.com/blog/computer-vision-powers-automatic-jigsaw-puzzle-solver>.