A Fully-Automated Solver for Multiple Square Jigsaw Puzzles Using Hierarchical Clustering

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- First jigsaw puzzle introduced in the 1760s. Modern jigsaw puzzles were introduced in the 1930s.
- First computation jigsaw puzzle solver introduced in 1964.
- Solving a jigsaw puzzle is NP Complete [1, 2]

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- **Example Applications:** DNA fragment reassembly, shredded document reconstruction, speech descrambling, and image editing.

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- First computation jigsaw puzzle solver introduced in 1964.
- Solving a jigsaw puzzle is NP Complete [1, 2]
- **Example Applications:** DNA fragment reassembly, shredded document reconstruction, speech descrambling, and image editing.
  - In most cases, the original, “ground-truth” image is unknown.

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Jigswap Puzzles – Variant of the traditional jig saw puzzle

- All pieces are equal-sized squares
- Substantially more difficult

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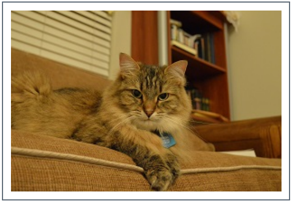

Ground-Truth Image

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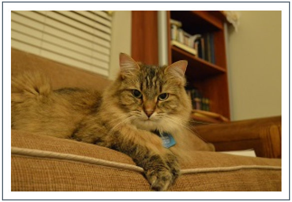

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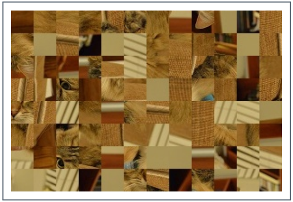

Randomized Jig Swap Puzzle

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There are four primary jig swap puzzle types as formalized by [3]. In all cases, the “ground-truth” input is unknown.

- **Type 1**: Puzzle dimension and piece rotation are known. One or more “anchor” pieces are fixed in their correct location.

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- **Mixed-Bag**: Pieces come from multiple puzzles.

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Mixed-Bag Puzzles are the focus of this thesis.

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- **Basis of all Modern Jig Swap Solvers**: The more compatible two pieces are on their respective sides, the more likely they are to be adjacent.
- **Best Buddies**: Any pair of puzzles pieces that are more compatible with each other on their respective sides than they are to any other piece [4]

$$\forall p_k \forall s_z, C(p_i, s_x, p_j, s_y) \geq C(p_i, s_x, p_k, s_z)$$
$$\text{and} \tag{1}$$
$$\forall p_k \forall s_z, C(p_j, s_y, p_i, s_x) \geq C(p_j, s_y, p_k, s_z)$$

- **Importance of Best Buddies**: Strong indicator of piece adjacency

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- **Cho *et al.*** [5] – Introduced the first Modern Jig Swap Puzzle Solver Introduced
  - Graphical model-based Type 1 solver
  - Puzzle dimensions are known
  - Used one or more anchor pieces
  - Defined solver output quality metrics
  - Established the standard comparative test conditions

Previous Work

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  - Graphical model-based Type 1 solver
  - Puzzle dimensions are known
  - Used one or more anchor pieces
  - Defined solver output quality metrics
  - Established the standard comparative test conditions
- **Pomeranz *et al.*** [4] – Iterative, greedy jigsaw Type 1 puzzle solver
  - Eliminated the use of anchor pieces
  - Created multiple solver benchmarks of various sizes
  - Introduced the concept of "best buddies"

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Paikin & Tal's Algorithm

- Begin each puzzle with a single piece
- Place all pieces around the expanding core

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Alternate Jigsaw Puzzle Solving Strategy

- Correctly assemble small puzzle regions (i.e., segments)
- Iteratively merge smaller regions to form large ones

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Alternate Jigsaw Puzzle Solving Strategy

- Correctly assemble small puzzle regions (i.e., segments)
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- **Advantage of this Approach**:
  - Reduces the size of the problem
  - Provides structure to the unordered set of puzzle pieces.

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The latter strategy is the basis of the **Mixed-Bag Solver**.

Quantifying Solver Quality

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- Jigsaw puzzle solvers are not yet able to always correctly reconstruct the input puzzle(s)
  - Metrics compare the quality of solved outputs
- **Two Most Common Quality Metrics**:
  - Direct Accuracy
  - Neighbor Accuracy

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- Jigsaw puzzle solvers are not yet able to always correctly reconstruct the input puzzle(s)
  - Metrics compare the quality of solved outputs
- **Two Most Common Quality Metrics**:
  - Direct Accuracy
  - Neighbor Accuracy
- **Disadvantages of Current Metrics**: Neither account for:
  - Pieces misplaced in different puzzles
  - Extra pieces from other puzzles
- **Goal**: Define new Mixed-Bag puzzle quality metrics.

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- **Direct Accuracy**: Fraction of pieces (c) placed in the same location in both the ground-truth and solved image with respect to the total number of pieces (n)

$$DA = \frac{c}{n} \tag{2}$$

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- **Enhanced Direct Accuracy Score (EDAS)**: Modified direct accuracy that accounts for missing and extra pieces.

$$EDAS_{P_i} = \operatorname*{arg\,max}_{S_j \in S} \frac{c_{i,j}}{n_i + \sum_{k \neq i}(m_{k,j})} \tag{3}$$

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Standard and Enhanced Direct Accuracy

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- **Direct Accuracy Range**: 0 to 1
- **Perfectly Reconstructed Image**: All pieces are placed in their original location ($DA = EDAS = 1$)

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- **Standard Direct Accuracy**: Fraction of pieces (c) placed in the same location in both the ground-truth and solved image versus the total number of pieces (n)

$$DA = \frac{c}{n} \tag{4}$$

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Problem: Direct accuracy is highly vulnerable to shifts, in particular when puzzle dimensions are not fixed

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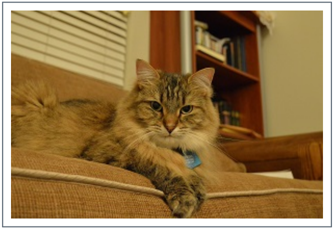

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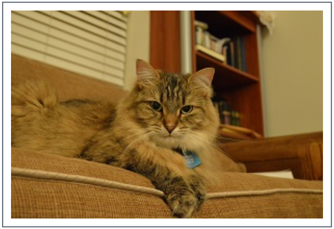

Ground-Truth Image

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Direct Accuracy

Effect of Shifts

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Conclusion: Direct accuracy can be overly punitive.

Direct Accuracy

Shiftable Enhanced Direct Accuracy Score (SEDAS)

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- **Solution**: Allow the reference point for direct accuracy to shift beyond the upper left corner of the image
- **Shiftable Enhanced Direct Accuracy Score (SEDAS)**: Select the reference point, l, within radius d_{min} of the upper left corner of the solved puzzle
  - d_{min} - Manhattan distance between the upper left corner of the solved image and the nearest puzzle piece
- **Formal Definition of SEDAS**:

$$SEDAS_{P_i} = \underset{l \in L}{\arg\max} \left(\underset{S_j \in S}{\arg\max} \frac{c_{i,j,l}}{n_i + \sum_{k \neq i}(m_{k,j})} \right) \qquad (6)$$

- **SEDAS Range**: 0 to 1

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- **Standard Neighbor Accuracy**: Ratio of puzzle piece sides adjacent in both the original and solved images (a) versus the total number of puzzle piece sides ($n \cdot q$)

$$NA = \frac{a}{n \cdot q} \tag{7}$$

Quantifying Solver Quality

Standard and Enhanced Neighbor Accuracy

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$$NA = \frac{a}{n \cdot q} \tag{7}$$

- **Enhanced Neighbor Accuracy Score (ENAS)**: Modified neighbor accuracy that accounts for missing and extra pieces.

$$ENAS_{P_i} = \operatorname*{arg\,max}_{S_j \in S} \frac{a_{i,j}}{q(n_i + \sum_{k \neq i}(m_{k,j}))} \tag{8}$$

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- **Standard Neighbor Accuracy**: Ratio of puzzle piece sides adjacent in both the original and solved images (a) versus the total number of puzzle piece sides ($n \cdot q$)

$$NA = \frac{a}{n \cdot q} \tag{7}$$

- **Enhanced Neighbor Accuracy Score (ENAS)**: Modified neighbor accuracy that accounts for missing and extra pieces.

$$ENAS_{P_i} = \underset{S_j \in S}{\arg\max} \frac{a_{i,j}}{q(n_i + \sum_{k \neq i}(m_{k,j}))} \tag{8}$$

- **Neighbor Accuracy Range**: 0 to 1
- **Advantage of Neighbor Accuracy**: Less vulnerable to shifts than direct accuracy

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- **Best Buddies Review**: Any pair of puzzles pieces that are more compatible with each other on their respective sides than they are to any other piece
  - **Note**: Not all puzzle pieces will have a best buddy.

- **Best Buddy Density** (BBD): A metric for quantifying the best buddy profile of an image that is independent of image size.

$$BBD = \frac{b}{n \cdot q} \tag{9}$$

- A greater BBD means the pieces are more differentiated making the puzzle easier to solve.

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Visualizing Best Buddy Density

- Transform each puzzle piece into a square consisting of four isosceles triangles.
- Color each triangle according to whether the adjacent piece is a best buddy. The scheme used in this thesis:

No Best Buddy	Non-Adjacent Best Buddy	Adjacent Best Buddy	No Piece Present
White	Red	Green	Black

- Areas with higher best buddy density will have more green triangles.

Best Buddy Density

Visualization Example

(a) Original Image [6]

Figure: Visualization of Best Buddy Density

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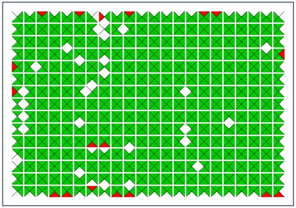
(a) Original Image [6]



(b) Best Buddy Visualization

Figure: Visualization of Best Buddy Density

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- Paikin & Tal's algorithm is the current state of the art and was used as the basis for all performance comparisons.

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- Paikin & Tal's algorithm is the current state of the art and was used as the basis for all performance comparisons.
- **Standard Test Conditions**
  - **Puzzle Type**: 2
  - **Dimensions Fixed**: No
  - **Piece Width**: 28 pixels
  - **Benchmark**: Twenty 805 piece images [**?**]
  - **Image Encoding**: LAB colorspace

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  - **Puzzle Type**: 2
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  - **Piece Width**: 28 pixels
  - **Benchmark**: Twenty 805 piece images [**?**]
  - **Image Encoding**: LAB colorspace
- **Number of Ground-Truth Inputs**: 1 to 5

# Puzzles	1	2	3	4	5
# Iterations	20	55	25	8	5

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- Paikin & Tal's algorithm is the current state of the art and was used as the basis for all performance comparisons.
- **Standard Test Conditions**
  - **Puzzle Type**: 2
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  - **Piece Width**: 28 pixels
  - **Benchmark**: Twenty 805 piece images [?]
  - **Image Encoding**: LAB colorspace
- **Number of Ground-Truth Inputs**: 1 to 5

# Puzzles	1	2	3	4	5
# Iterations	20	55	25	8	5

- **Test Condition Variation**: Only Paikin & Tal's algorithm was provided the number of input puzzles.

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- **Goal**: Measure the Mixed-Bag Solver's accuracy determining the number of input puzzles
  - **Importance** – The Mixed-Bag Solver must estimate this accurately to provide meaningful outputs.

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- **Goal**: Measure the Mixed-Bag Solver's accuracy determining the number of input puzzles
  - **Importance** – The Mixed-Bag Solver must estimate this accurately to provide meaningful outputs.
- **Two Subexperiments**:
  - **Single Puzzle Accuracy** – This represents the solver's performance ceiling
  - **Multiple Puzzle Accuracy** – A more general estimate of the solver's performance

Determining Input Puzzle Count

Single Input Puzzle Results

- **Summary**: 17 out of the 20 images were correctly identified as a single ground-truth input
- **Misclassified Images**: 3 out of the 20 images misclassified as if they were two images.
  - All three images have large areas with little variation (e.g., blue sky, smooth water)
  - The solver's performance on these puzzles is due to the assembler as noted in [7]

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Single Input Puzzle Results

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- **Summary**: 17 out of the 20 images were correctly identified as a single ground-truth input
- **Misclassified Images**: 3 out of the 20 images misclassified as if they were two images.
  - All three images have large areas with little variation (e.g., blue sky, smooth water)
  - The solver's performance on these puzzles is due to the assembler as noted in [7]
- **Note**: 85% (17/20) represents the maximum accuracy when solving multiple puzzles.

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Comparison of Best Buddy Density for Misclassified Images

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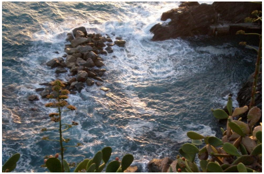

Perfectly Reconstructed Image (a)

Misclassified Image (b)

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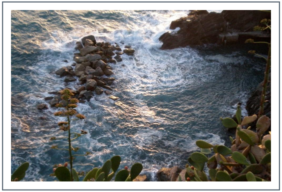
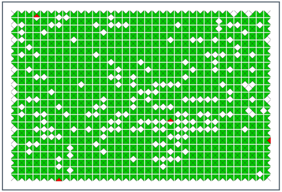
Comparison of Best Buddy Density for Misclassified Images

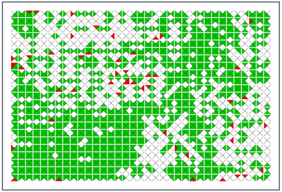


Perfectly Reconstructed Image (a)



Best Buddy Visualization (a)

Misclassified Image (b)



Best Buddy Visualization (b)

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- **Goal**: Measure the Mixed-Bag Solver's accuracy determining the input puzzle count for multiple images

- **Procedure**: Randomly select the specified number of images (between 2 and 5) from the 20 image data set.

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- **Goal**: Measure the Mixed-Bag Solver's accuracy determining the input puzzle count for multiple images
- **Procedure**: Randomly select the specified number of images (between 2 and 5) from the 20 image data set.
- **Input Puzzle Count Error**: Difference between the actual number of input puzzles and that found by the Mixed-Bag Solver.
  - **Example**: If 3 images were supplied to the solver, but it determined there were 4, the error would be 1.

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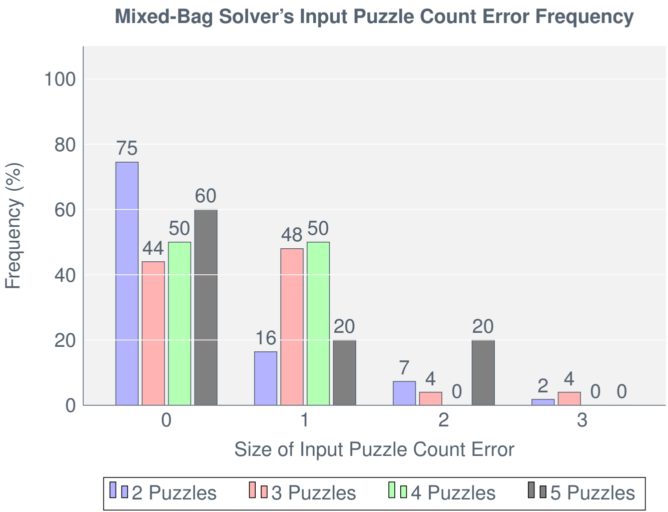

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- **Overall Accuracy**: 65%
- **Iterations with Error Greater than One**: 8%
- Accuracy did not significantly degrade as the number of input puzzles increased.

Determining Input Puzzle Count

Multiple Input Puzzles – Results Summary

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- **Overall Accuracy**: 65%
- **Iterations with Error Greater than One**: 8%
- Accuracy did not significantly degrade as the number of input puzzles increased.
- **Over-Rejection of Cluster Merges**: The Mixed-Bag Solver never underestimated the number of input puzzles.
  - Performance may be improved by reducing the minimum clustering similarity threshold or minimum segment size

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- **Goal**: Compare the performance of the Mixed-Bag Solver and Paikin & Tal's algorithm
- **Procedure:** Randomly select a specified number of images and input them into both solvers.
- **Quality Metrics Used**:
  - Shiftable Enhanced Direct Accuracy Score (SEDAS)
  - Enhanced Neighbor Accuracy Score (ENAS)
  - Perfect Reconstruction Percentage

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Performance Comparison on Multiple Input Puzzles

- **Goal**: Compare the performance of the Mixed-Bag Solver and Paikin & Tal's algorithm
- **Procedure:** Randomly select a specified number of images and input them into both solvers.
- **Quality Metrics Used**:
  - Shiftable Enhanced Direct Accuracy Score (SEDAS)
  - Enhanced Neighbor Accuracy Score (ENAS)
  - Perfect Reconstruction Percentage
- **Note**: The results include the Mixed-Bag Solver's performance when it correctly estimated the puzzle count.
  - This represents the performance ceiling for optimal hierarchical clustering.

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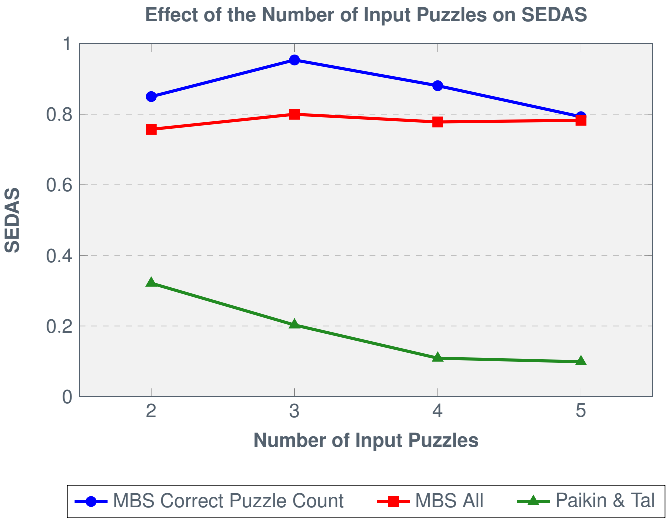
Performance on Multiple Input Puzzles

Shiftable Enhanced Direct Accuracy Score (SEDAS)



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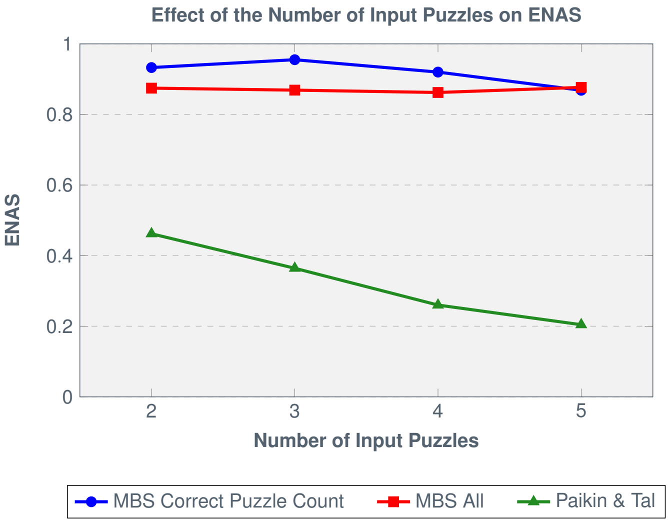

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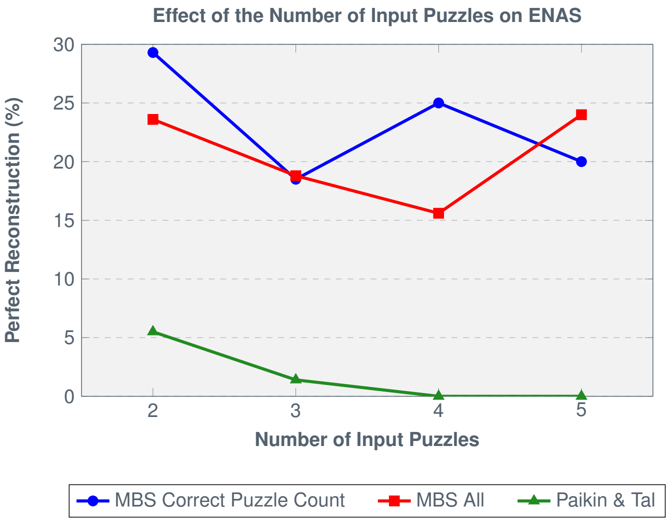

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- **Summary**: The Mixed-Bag Solver significantly outperformed Paikin & Tal's algorithm across all metrics.
  - This is notwithstanding that only their algorithm was supplied with the number of input puzzles.

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- **Summary**: The Mixed-Bag Solver significantly outperformed Paikin & Tal's algorithm across all metrics.
  - This is notwithstanding that only their algorithm was supplied with the number of input puzzles.
- **Puzzle Input Count**: Unlike Paikin & Tal's algorithm, the Mixed-Bag Solver saw no significant decrease in performance with additional input puzzles

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- **Summary**: The Mixed-Bag Solver significantly outperformed Paikin & Tal's algorithm across all metrics.
  - This is notwithstanding that only their algorithm was supplied with the number of input puzzles.
- **Puzzle Input Count**: Unlike Paikin & Tal's algorithm, the Mixed-Bag Solver saw no significant decrease in performance with additional input puzzles
- **Effect of Clustering Errors**: Performance only decreased slightly when incorrectly estimated input puzzle count.
  - Many of the extra puzzles were relatively insignificant in size

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- As the number of puzzles increases, the difficulty of simultaneously reconstructing them also increases.

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Solving More than Five Puzzles

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- As the number of puzzles increases, the difficulty of simultaneously reconstructing them also increases.

- **Current State of the Art**: Paikin & Tal [7] solved up to five puzzles simultaneously.

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- As the number of puzzles increases, the difficulty of simultaneously reconstructing them also increases.
- **Current State of the Art**: Paikin & Tal [7] solved up to five puzzles simultaneously.
- **Goal**: Compare the performance of the Mixed-Bag Solver and Paikin & Tal's algorithm on 10 puzzles.

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- **Paikin & Tal**
  - Seed of nine images came from just three input images
  - SEDAS and EDAS greater than 0.9 for only one image
  - No perfectly reconstructed images

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- **Paikin & Tal**
  - Seed of nine images came from just three input images
  - SEDAS and EDAS greater than 0.9 for only one image
  - No perfectly reconstructed images
- **Mixed-Bag Solver**
  - SEDAS and EDAS greater than 0.9 for all images
  - Four images perfectly reconstructed
  - Results comparable to Paikin & Tal's algorithm solving each puzzle individually

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- **Paikin & Tal**
  - Seed of nine images came from just three input images
  - SEDAS and EDAS greater than 0.9 for only one image
  - No perfectly reconstructed images
- **Mixed-Bag Solver**
  - SEDAS and EDAS greater than 0.9 for all images
  - Four images perfectly reconstructed
  - Results comparable to Paikin & Tal's algorithm solving each puzzle individually
- **Conclusion**: The performance difference between the Mixed-Bag Solver and Paikin & Tal's algorithm is even starker with more input puzzles.

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- This thesis presented a fully-automated solver for Mixed-Bag jig swap puzzles.
- Mixed-Bag Solver significantly outperforms the current state of the art while receiving no externally supplied information.
- Introduced the first set of solver quality metrics for Mixed-Bag puzzles.

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- Improved Assembler
  - Prioritize placement using multiple best buddies

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- Improved Assembler
  - Prioritize placement using multiple best buddies
  - Address placement performance in regions with low best buddy density
- Dynamic determination of the segment clustering threshold

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A Fully-Automated Solver for Multiple Square Jigsaw Puzzles Using Hierarchical Clustering

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List of References I

[1] T. Altman, "Solving the jigsaw puzzle problem in linear time," *Applied Artificial Intelligence*, vol. 3, pp. 453–462, Jan. 1990.

[2] E. D. Demaine and M. L. Demaine, "Jigsaw puzzles, edge matching, and polyomino packing: Connections and complexity," *Graphs and Combinatorics*, vol. 23 (Supplement), pp. 195–208, June 2007.

[3] A. C. Gallagher, "Jigsaw puzzles with pieces of unknown orientation," in *Proceedings of the 2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, CVPR '12, pp. 382–389, IEEE Computer Society, 2012.

[4] D. Pomeranz, M. Shemesh, and O. Ben-Shahar, "A fully automated greedy square jigsaw puzzle solver," in *Proceedings of the 2011 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, CVPR '11, pp. 9–16, IEEE Computer Society, 2011.

[5] T. S. Cho, S. Avidan, and W. T. Freeman, "A probabilistic image jigsaw puzzle solver," in *Proceedings of the 2010 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, CVPR '10, pp. 183–190, IEEE Computer Society, 2010.

[6] H. Braxmeier and S. Steinberger, "Pixabay." `https://pixabay.com/`. (Accessed on 05/15/2016).

[7] G. Paikin and A. Tal, "Solving multiple square jigsaw puzzles with missing pieces," in *Proceedings of the 2015 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, CVPR '15, IEEE Computer Society, 2015.