



# Assembling Fragments of Ancient Papyrus via Artificial Intelligence

Eugenio Vocaturo<sup>1,2</sup>(✉)  and Ester Zumpano<sup>1,2</sup> 

<sup>1</sup> DIMES, University of Calabria, Arcavacata, Italy  
{e.vocaturo,e.zumpano}@dimes.unical.it

<sup>2</sup> CNR-Nanotec, Rende, CS, Italy

**Abstract.** The knowledge of humanity passes through the ancient texts whose acquisition, reconstruction and interpretation become tasks of fundamental importance. The simultaneous spread of equipment capable of exploiting new technologies for data acquisition together with the opportunities offered by Artificial Intelligence open new unimaginable horizons in different applications including the conservation of cultural heritage. In this work, we refer to the opportunity inherent the acquisition of texts from papyri via machine learning and deep learning applications. The theme of assembling fragments, will be investigated by referring to some recent interesting contributions of the scientific community.

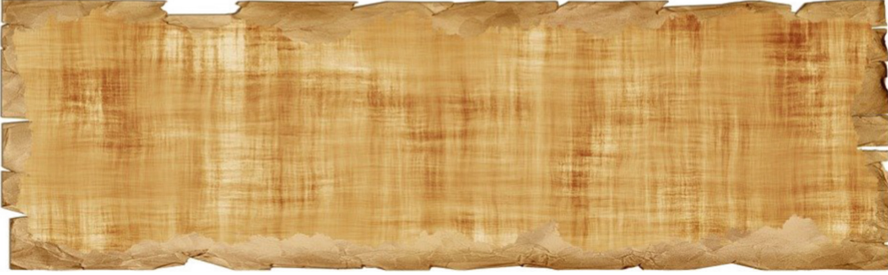
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## 1 Introduction

Archaeologists use ancient documents to investigate the organization of ancient human societies. In particular, the objective is to understand the customs, cultural, social and economic aspects of the daily life of the people who were alive at the time of the drafting of the documents. The discovery of manuscripts is always an extraordinary event that brings to light documents dating back many centuries ago. Manuscripts inevitably undergo a natural process of erosion aggravated by various other factors both related to the nature of the papyrus and the inks used and to atmospheric agents. Papyrus was one of the typical materials used since the dawn of time as a support for writing. Papyrus was a real revolution in ancient world science, and was produced using sophisticated techniques from the stems of the papyrus plant (*Cyperus papyrus*).

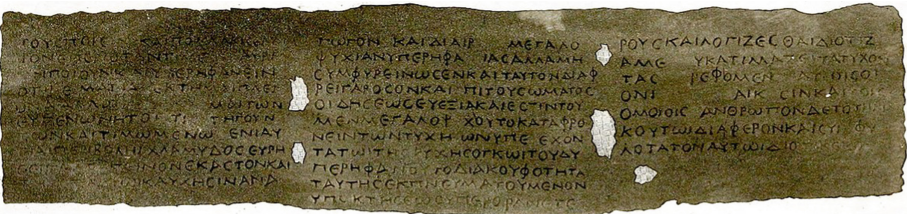
A unique type of paper is produced by extracting marrow threads from the stem and using them to create a specific pattern of warp and weft [36]. The ancient process of making this paper involved layering papyrus pith strips and gluing them together so that the strips in each layer are perpendicular to each other. The layers were then smoothed to achieve the desired surface finish and dried before being ready for writing [26]. The text was commonly written on

the side of the papyrus with horizontal threads, named *Recto*, aligning with the thread lines, but in some cases, the back of the papyrus, named *Verso*, with vertical threads was also used for writing [6]. The production technique adopted involved local weaving patterns that characterized adjacent portions of the papyrus with a certain similarity [18] (Fig. 1).



**Fig. 1.** Structure of the Papyrus: horizontal threads (*Recto*) and vertical threads (*Verso*).

The way that papyri are made supports the idea that researchers who work with fragment alignment can rely on certain characteristics to match fragments. These researchers typically assume that fragments found in the same area will have similar visual features such as thread width, direction, spacing, and frequency. Analyzing the content of ancient papyri is challenging because it requires piecing together fragments of documents without knowing which fragments belong to the same document. This is similar to trying to complete a puzzle without knowing which pieces belong to which puzzle or if all the pieces are even present. With thousands of fragments from different documents, the task of reconstructing them can be time-consuming and labor-intensive. Recent opportunities offered by artificial intelligence allow the definition of support frameworks for the automatic reconstruction of ancient papyri (Fig. 2).



**Fig. 2.** Papyrus 27 of Ercolano.

Extreme challenges are faced in this domain, such as the management of the charred papyri of Herculaneum for which advanced approaches are being defined to simulate the virtual unrolling of papyri, which otherwise could not be treated. The bundles of papyrus rolls were scorched by the pyroclastic flows' tremendous heat during Vesuvius' eruption in 79 AD [1] (Fig. 3).



**Fig. 3.** Charred papyrus roll.

This intense overheating occurred in an extremely short period of time and in oxygen-poor environments, causing the rolls to carbonise into compact and extremely brittle blocks. Later they were covered and preserved by layers of extremely tenacious lava rock. Having to face these new challenges has prompted researchers to adopt new instruments for reading the papyri.

Terahertz time domain spectroscopic imaging (THz-TDSI) is an example of a non-destructive, non-ionizing measuring method that has lately been used to examine items from cultural heritage. In [25], the authors describe this method as well as the outcomes of non-contact measurements of papyrus texts, including pictures of concealed papyri. The historical binder, Arabic gum, and two typical pigments used to write ancient writings, carbon black and red ochre, were combined to create inks for current papyrus examples. The samples were scanned with a pulse with a spectral range between 0.1 and 1.5 THz in reflection at normal incidence. The depths of the layers are determined by the signals' temporal analysis, and the inks' frequency spectra are revealed by the signals' frequency spectra. In [5], the authors used an improved X-ray phase-contrast tomography non-destructive technology and a new set of numerical algorithms for "virtual - unrolling" to decipher several passages of text concealed inside carbonized Herculaneum papyri. In unopened scrolls, they were able to detect the greatest chunk of Greek text ever with previously unheard-of spatial resolution and contrast, all without causing any harm to these priceless ancient texts. The 'voice' of the Epicurean philosopher Philodemus is revived from Herculaneum papyri thanks to portions of the text that have been decrypted.

The paper is structured as follows: in Sect. 2 assembling fragments task will be recalled, referring to the related problems and to the first approaches with which the scientific community has begun to deal with the topic. In Sect. 3, we

will refer to different machine learning and deep learning proposals, highlighting the strengths and weaknesses of the various proposals. The goal is to provide a meaningful overview for the reader who approaches to dealing with the issues of assembling fragments. Finally, in the last section we draw conclusions on the approaches and report specific open challenges to be faced.

## 2 Applications for Assembling Fragments

In this work, we refer to the opportunity inherent the acquisition of texts from papyri via artificial intelligence applications focusing to the particular issue of assembling fragments. The task of reconstructing a document by repositioning its fragments plays a key rule in archeology.

Given that two portions of various papyri might appear to be identical since they were written by the same person with the same ink and have a comparable level of wear, the challenges are especially pernicious. Because labeled data is uncommon, frequently uneven, unbalanced, and of irregular conservation statuses, it is difficult to automate using machine learning methods. However, the papyrology community has a real need for such software because manually reconstructing the papyri takes a lot of time and effort. Through artificial intelligence applications, the scientific community proposes solutions to overcome the manual coupling phases to assemble rolls as large and complete as possible.

In general, fragments of papyri that are discovered are often in poor condition due to degenerative processes such as erosion. Additionally, these fragments are typically very small and the writing on them is often scattered and fragmented: all these premises imply that pairing based on writing alone can easily fail: pairing based solely on geometric features, known as *pictorial approach*, is impractical.

The first works proposed by the scientific community, dating back to the 1960s, tried to use geometric features, such as shape, contours, curvature, of the fragments to be able to reconstruct the documents. The evolution of these approaches has resulted in proposals based on partial curve matching techniques that involve the use of only a small fraction of their boundaries [23]. However, the proposals based only on the exploitation of geometric features showed their limits when the documents to be recreated were large and the number of fragments to be recomposed is high.

A subsequent step for solving the puzzles dates back to the 90s, when greater importance was given [24] to the plot, scripts and drawings and also referring to the possibility of exploiting new metrics deriving from representation in different color spaces. In the study “Jigsaw puzzle solving using chromatic information” [17], the authors showed that incorporating color information can enhance the ability to solve puzzles by utilizing the color values of the boundary pixels and using them to match the boundary data of the image. The approach of exploiting the chromatic information of the points or of some sub-regions of the images in relation to those of the neighboring portions has given, among other things, important results in the analysis of images in the medical domain [19, 41, 42].

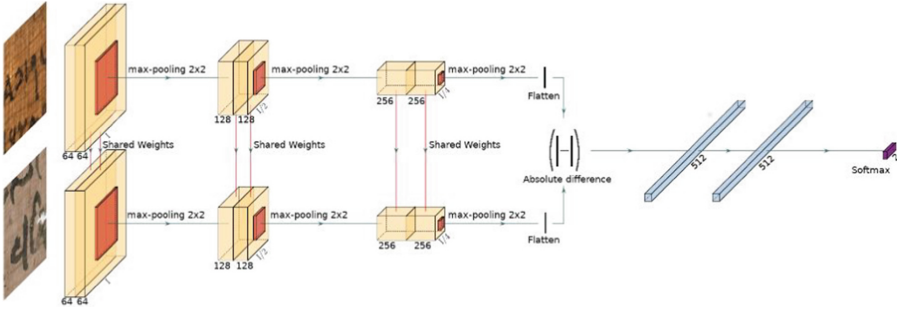
In recent years, drawing on the pool of opportunities of different machine learning and deep learning models, different solutions have been presented to combine archaeological fragments.

The authors of [38] provided a comprehensive approach for the color-based automatic reassembly of 2-D picture fragments. Four phases make up the proposed 2-D reassembly approach. Initially, approaches used in content-based image retrieval systems are used to identify picture fragments that are geographically nearby. The second procedure entails using a dynamic programming approach to locate the matching contour segments for each preserved pair of picture fragments. Finding the best transformation to align the appropriate border segments is the following step. The entire image is then pieced back together using its appropriately positioned components. The suggested approach was evaluated using digitally scanned photographs of ripped pieces of paper, and the results of the reassembly were quite good. Each step of the suggested technique might be improved by utilizing textual or semantic qualities in addition to color.

In [37], the authors describe a multipurpose method for figuring out the relationships between tiny pieces of ancient artifacts, such frescoes from the Bronze and Roman eras. The authors offer a collection of feature descriptors that are based not just on color and form but also on normal maps, in contrast to conventional 2D and 3D shape matching algorithms. These combine great data quality with discriminability and resistance against specific forms of degradation, and they are simple to gather. The new feature descriptors are easy to compute and match and vary from generic to domain-specific. The method was evaluated on three datasets of fresco pieces, illustrating how distinct trade-offs between efficiency and effectiveness result from multi-cue matching utilizing various subsets of features. The authors specifically show that 3D features are more discriminative than 2D or normal-based features, albeit at a greater computational cost, and that normal-based features are more effective than color-based features at equivalent computational complexity.

In [33], the authors use an unsupervised genetic algorithm to solve the search challenge by creating a collection of incomplete reconstructions that expands via recombination and selection over several generations. A new selection method that balances fitness and diversity in the population was developed for integrating incomplete reconstructions. This algorithm is resilient to noise and outliers. The suggested technique outperforms earlier automated systems in tests using a benchmark dataset by producing bigger and more precise global reconstructions. The weakness of this idea is that it lacks the strongest argument inherent in scarcity circumstances despite having dealt with nearly all enigmas.

The scarcity of samples and the complexity of the tasks to be tackled has so far constituted a great obstacle for effective proposals for correspondence of the papyrus. Some interesting proposals are based on the attempt to borrow image management techniques from other application contexts. In [30], Papy-S-Net is proposed for identify papyrus “spots” belonging to the same fragment. Through a Siamese neural network, which has two identical branches with shared weights during training and prediction, patches are coupled with intriguing outcomes (Fig. 4).



**Fig. 4.** The architecture of Papy-S-Net [30].

When input is given, each branch determines a functional vector. The input images are of size  $128 \times 128 \times 3$ , each pooling operation (red squares) divides the dimension of the images by 2, each convolution operation uses a kernel of size  $3 \times 3$ .

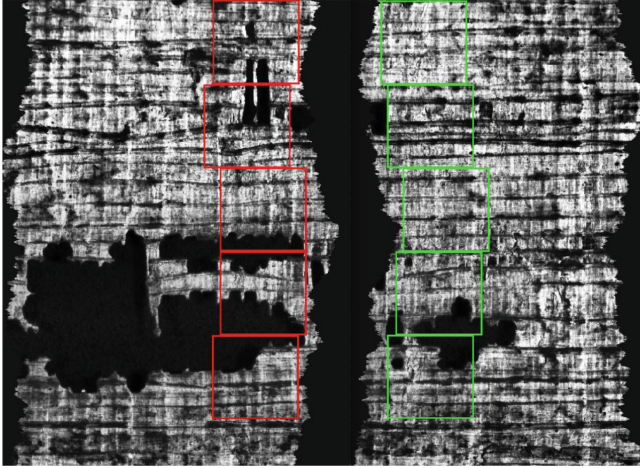
Everywhere in the method save the top layer-which utilizes Softmax for binary classification-relies on ReLU activation functions. The outputs from the two branches are merged by calculating the absolute value of the element-wise difference between each branch's flattened outputs. The weights of the two branches are shared. The Softmax two-layer fully-connected network is then given this vector: 500 papyrus pieces are used to train and evaluate the chosen network. The authors contrast Papy-S-findings Net's with a prior study by Koch et al. [22], which suggests a siamese network to correspond with written symbols. The extraction of patches from the papyrus pieces to form the ground truth was offered in order to train and validate the network. The suggested method was also tested in practice, with Papy-S-Net achieving 79% of accurate matches. This proposed approach is interesting even if the real challenge is the matching of fragments that exhibit a significant gaps between them. If on the one hand the outlines of the papyrus fragments are malformed, on the other hand their manufacturing technique allows to intercept pictorial information according to the pattern of the plots.

In [2], the authors presented an extremely intriguing solution: the algorithm is predicated on the idea that the thread patterns of papyrus have distinctive local characteristics, leading surrounding pieces to exhibit patterns resembling the threads' continuations. The suggested algorithm and system facilitate both the geometric alignment of the matched pairs of papyrus fragments against one another as well as the rapid and automatic categorization of the pairings. The concept is broken down into many phases and is based on machine learning and deep learning techniques. In order to discover thread continuation matches in the local edge regions (squares) between pairs of fragments, the challenge of matching fragments must first be broken down into smaller problems.

A convolutional neural network is used to solve this stage by ingesting raw pictures of the edge regions and providing local matching scores. By creating a

complex voting system, the authors use these scores to draw conclusions regarding the matching of complete fragment pairings.

All of the information gathered from these processes is fed into a Random Forest classifier to create a higher order classifier that can determine whether a pair of fragments matches or not. The suggested technique was developed using a set of Dead Sea cave artifact fragments that were dated to the first century BCE. On a validation set with a similar origin, the algorithm displays great results (Fig. 5).



**Fig. 5.** Two adjacent artificially torn fragments with candidate squares for the matching phase [2]

The need to be able to dispose of discriminatory features with respect to the available data is pushing the community towards the adoption of deep learning models [27]. In general, also the number of classes in which the fragments will have to be classified is not known *ex ante*; therefore, the impossibility of using standard deep learning classification schemes suggested the adoption of deep metric learning (DML) methods.

In order to get a high score for two fragments from the same text and a low score for two fragments from separate documents, in [31] the authors employ a DML model. A comparable sample is considered to be near in terms of a metric geometric distance, such as the Euclidean distance, by the DML model, which learns the pertinent characteristics to be extracted and projects them into a latent space. As opposed to more “conventional” deep learning classification approaches, this method does not require knowledge of the number of classes in order to rebuild the document. The authors of this paper investigate how papyrologists can use Deep Convolutional Siamese-Networks to obtain useful matching suggestions on new data. They demonstrate that the from-scratch self-supervised approach is superior to using knowledge transfer from a large

dataset, with the former attaining a top-1 accuracy score of 0.73 on an 800 fragment retrieval challenge.

In [20] the authors introduced a variant of Siamese networks known as Triplet Networks. This technique does away with similar and dissimilar pairings in favor of assigning the network a triplet made up of an Anchor sample, a positive sample, and a negative sample. In comparison to losses that take into account comparable and dissimilar samples individually, the optimization of a loss function based on the distance between Anchor/Positive and Anchor/Negative at each iteration enhances intra-class compactness and separability between classes [21]. By choosing the triplets functional to convergence in a certain training phase, the batch-hard and batch-all mining techniques enable learning process optimization. The availability of annotated data is not yet sufficient to ensure generalization in training deep learning models. This justifies why the community currently tends to adopt solutions that employ transfer learning or domain adaptation, as in [34,35], or that employ unsupervised learning [16], semi-supervised [32] or self-supervised [28,29].

When using self-supervised frameworks, trainable pretext activities are often initially generated from the raw unlabeled data. Models are compelled to learn practical representations related to the intended job by the pretext activities. The authors of [16], for instance, employ grouped SIFT descriptors as pretext activity labels to get the writer's name while retrieving information on papers. Instead, the authors of [29] train a model to reassemble mixed shredded text documents after producing disrupted documents.

### 3 Conclusion

Artificial intelligence applications are taking over in the cultural heritage community, resulting in the presentation of various proposals and sophisticated techniques for sensitive tasks such as those involving the activity of assembling fragments and more in general the recognition of historical documents [3,4,39]. We have examined some interesting proposals that adopt, from a methodological point of view, convolutional layer architectures capable of exploiting large amount of labeled data. Even the data sets that are gradually presented begin to be numerous and are made up of new types of documents from different areas of the world. The specificity of the contexts to be analyzed is stimulating the design of new architectures also using models initially proposed for other tasks in other fields. In general, deep learning-based methods show interesting performance.

The main challenge is the potential lack of diverse, reliable, and enough data needed to train deep learning models. Due to the unique characteristics of the documents, the analysis of historical documents is really an area of study that is defined by a relative lack or absence of good quality data.

The design of robust and scalable techniques for historical documents analysis seems to be the way that could give a breakthrough for artificial intelligence applications in this research area. It should not be underestimated that historical documents often also contain graphic information and numerical values.

The use of architectures developed in other research areas, such as the medical industry, where context-specific features [9] are exploited by machine learning algorithms [40, 41], is a promising avenue that may be pursued. A significant barrier to the adoption of deep learning models is the requirement for vast amounts of training data, as well as the diminished explainability of the acquired findings and some level of skepticism among domain experts.

To this end a contribution in the direction of creating trusted and explainable AI and can be also provided by supporting machine learning framework with logic approaches [7, 8, 10] and adopting distributed techniques for data integration in cultural heritage domain [11–15].

In general, this is a typical criticality of deep learning models already encountered in other fields involving image analysis such as the medical one, where, for example, the results provided by frameworks based on deep learning models are viewed with great skepticism by specialists. Probably being able to identify a topic of interest could concentrate the community's efforts by pushing towards the creation of models that lend themselves to being generalized. In general, the application of artificial intelligence models and techniques is destined to range even in contexts different from those of assembling fragments of ancient papyrus, thus giving new life to many research areas concerning the conservation of cultural heritage [3, 4, 39].

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