Semantic Mapping of Architectural Heritage via Artificial Intelligence and H-BIM

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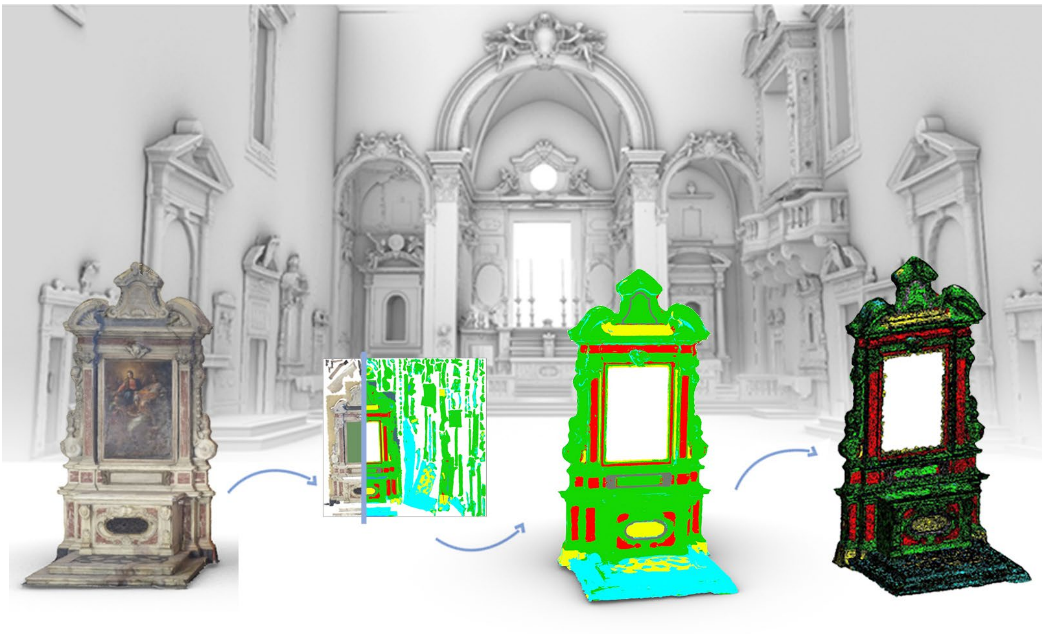
Abstract

Starting from the virtual photogrammetric 3D reconstruction, this work proposes a classification method, based on Artificial Intelligence, allowing to semi-automatically characterize the digital models of existing architectural heritage in terms of material mapping and/or decay condition. The obtained data, once classified, is used and transferred in BIM environment, so to favor the construction of informative models rich in analytical content. The proposed approach is described with reference to the significant case study of the Chiesa del Carmine in Pisa, for the study and restitution of the liturgical and decorative apparatus, as part of a large-scale research project, still underway, on the reconstruction of the tramezzo screens for the churches of the Mendicant orders.

Keywords
cultural heritage, classification, artificial intelligence, BIM, H-BIM, Chiesa del Carmine.



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Introduction

Nowadays, the digital documentation of architectural heritage necessarily requires the integration of different types of representation and the organization of information on different levels, for adequate restoration and conservation operations [Pamart et al. 2020]. Semantic segmentation techniques relying on Artificial Intelligence (AI) are emerging as privileged tools to appropriately organize, structure and classify the complex system of analytical and survey data related to an architectural object or site [Croce et al. 2021a].
In this paper, semi-automatic classification methods are exploited in order to associate the different semantic and descriptive information to the raw outputs of the three-dimensional survey, and Heritage-Building Information Modeling (H-BIM) systems are later considered to display and share the results. The case study on which the methodological approach is tested is the Chiesa del Carmine (Fig. 1), a church of the Mendicant order in Pisa (Italy): the classification is performed on the liturgical decorative apparatus of the church, and the textured meshes of the altars are analyzed so as to characterize the state of preservation of these objects, in particular with regard to the mapping of materials and decays [1][2][3].

State-of-the-Art

In the Cultural Heritage domain, an appropriate organization of unstructured 3D data derived from surveying is nowadays demanded. Classification techniques relying on geometry-based or texture-based approaches are emerging to semi-automatically organize, structure and interpret raw surveying information [Cera, Campi 2021], either characterizing the architectural object based on its geometric properties [Croce et al. 2021b] or on its colors or patterns [Grilli, Remondino 2019], respectively. Texture-based approaches, in detail, are demanded in cases where metric data alone are not sufficient to satisfy the tasks of description of a certain surface, e.g., if maps of degradation, surface alterations and materials are to be derived from the digital data. The Random Forest, a supervised Machine Learning algorithm, has been tested in [Matrone et al. 2020] as an effective method, applied on a case-by-case basis, for the automated classification of images, ortho-photos or UV maps starting from a suitable set of previously annotated

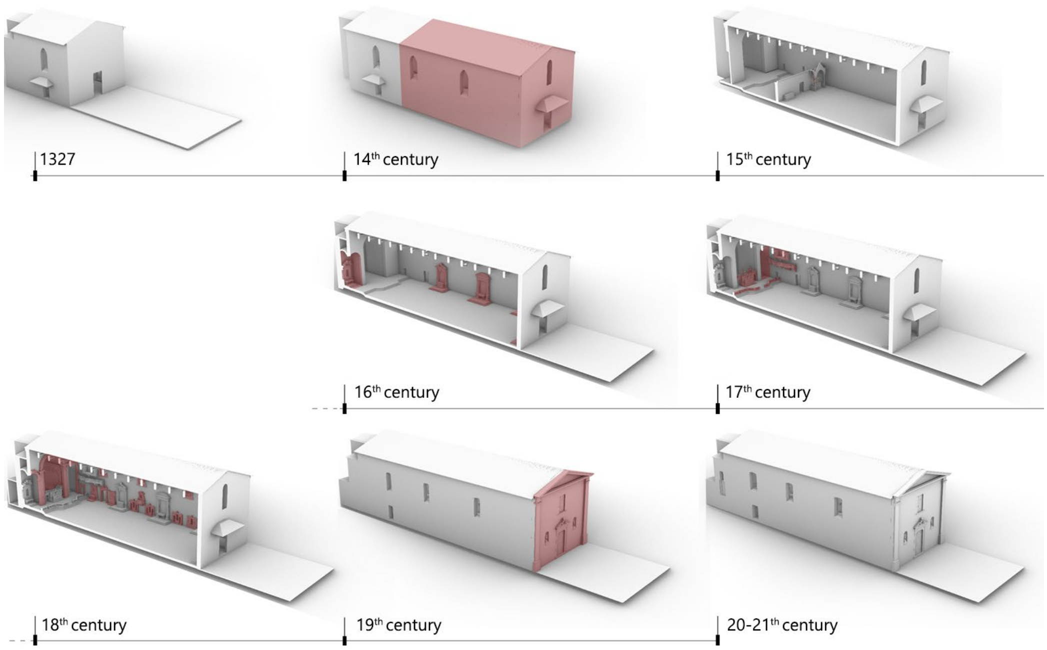

Fig. 1. Evolution of the Church over time.

data (training set). [Adamopoulos 2021] classified superficial damages on built cultural heritage even integrating multispectral data acquisition and supervised machine learning-based image segmentation, while [Murtiyoso et al. 2022] further investigated the use of semantic classification at the beginning of the classical photogrammetric workflow.
The classified digital data obtained can be leveraged in view of the construction of BIM-type information models for heritage objects [Croce et al. 2021], so facilitating the automatic identification of historical architectural elements and fostering the Scan-to-BIM process [Morbidoni et al. 2020].

The Church of Santa Maria del Carmine

The Church of Santa Maria del Carmine in Pisa was built by the Carmelitan monks in 1323, following their transfer within the urban walls of the city. Over the centuries, nationwide commissions have been involved in the construction and evolution of the church, so contributing to the achievement of its current architectural layout.
The church is composed of a single nave, covered by a gable roof. The enrichment of the internal decorative face dates back to the 17th century: along the side and back walls of the church, sumptuous baroque altars stand, placed on raised floors and closed by two columns, mounted on a base, which flank the altar table and conclude with a variously shaped crowning.

Fig. 2. 3D model of the Church's interiors, in the current layout.

Fig. 3. From left to right: Sparse point cloud; dense point cloud; mesh; textured model of the Altar of Santa Vittoria.

Fig. 4. Mesh models of some altars and decorative parts of the Church's interiors.

The analysis and study of the decorative liturgical apparatus of the church (Fig. 3) was part of the project of investigation on the location and arrangement of the 15th century *tramezzo* screen – i.e., the architectural partition typical of the churches of the Mendicant orders that transversally divided the church's nave, then removed following the Council of Trent (1545-1569) – inserted in a wider research work entitled "Seeing Below the Surface: Reconstructing Tramezzo Screens at San Francesco, Santa Caterina and Santa Maria del Carmine in Pisa" and conducted by a research group of the University of Pisa in collaboration with the University of Cambridge (UK), the University Suor Orsola Benincasa of Naples and the University of Padua.
Besides the work concerning the hypothetical reconstruction and the positioning of the *tramezzo* screen based on historical and archival information, the baroque altars of the Church were subject of an in-depth study on the mapping of decay and materials, which saw the application of most recent Artificial Intelligence and BIM modeling techniques.

Evolution of the Church Over Time

Undertaking a path aimed at deepening the knowledge of the artefact proved to be an essential support for the proposal of an integrated methodology that converged in the realization of a BIM Model, based on an initial laser scanner survey. A bibliographic and archival research first allowed to reconstruct the evolution of the church, as well as the changes and integrations of its decorative liturgical apparatus and architectural layout, over time.
For the construction of the study model displaying the temporal states of the church over the centuries (Fig. 1), perimetral walls, floor and roofs were preliminary traced over the original point cloud as BIM components, so to create the exterior building shell, in a Scan-to-BIM logic. Then, in order to virtually represent and describe the actual complexity of the liturgical apparatus of the church, the integration of reverse engineering techniques was considered: the altars and confessionals were segmented from the laser scanned point cloud, reconstructed as mesh models and later imported within the BIM platform Autodesk Revit (Fig. 4).

Study of the Liturgical Apparatus

A further, deeper level of analysis concerned the description of the liturgical apparatus of the Church: to this task, the integration with photogrammetric survey techniques was taken into account, so to better represent the radiometric (color) properties and decorative patterns of the Baroque altars and confessionals of the Church's interiors. For the latter, the results of photogrammetric 3D reconstruction technique were used to test the semi-automatic mapping of materials and decay conditions via AI (Fig. 5): in detail, the UV maps extracted from the textured mesh models were considered for the semantic segmentation task. On this bi-dimensional information, a supervised Machine Learning (ML) algorithm was applied in order to read, classify and return different degrees of degradation and/or types of materials of the altars.

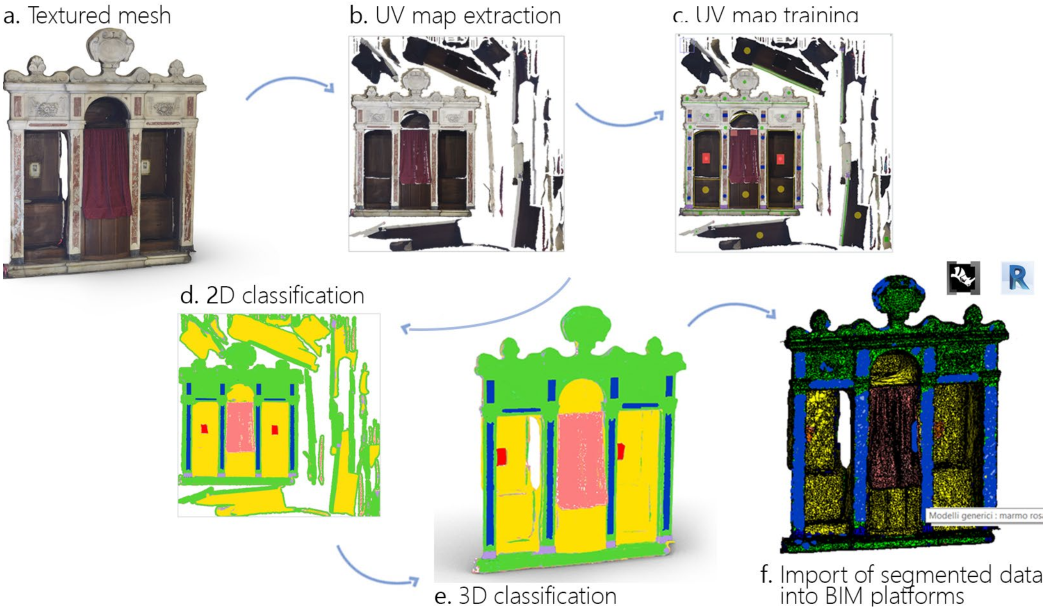

Fig. 5. Steps of the proposed methodology for the AI-based classification of the liturgical decorative apparatus.

The obtained distinction into classes of decay or types of material was preserved even at a final stage, when the classified mesh models derived from the segmentation process were inserted within specific H-BIM platforms, in a Scan-to-BIM application. To this end, portions of mesh having different material and degradation characteristics were imported into BIM platforms thanks to visual programming algorithms.

AI-Based Classification of Decay and Materials

A photogrammetric 3D model was obtained for the altars and confessionals composing the interior décor of the Church.
From the textured mesh of each surveyed object, and through the control of the seam lines, the UV maps were exported and later annotated in 2D to start the semantic segmentation process. The classes of materials or the levels of the degradation were identified and annotated over a reduced portion of data, to constitute a set of samples on which the ML model was trained. The training data was also supported by the so-called features, i.e., radiometric characteristics of data allowing the distinction between one class and another [Weinmann 2016].
A predictive model (Random Forest) is then trained on these data so as to foresee and map the classification of the entire dataset. As an example, the classes identified for Fig. 6 relate to the semantic mapping of materials. The paintings of the altar (the canvas material) are manually excluded from the classification, since trivial to segment over the UV map. Then, the different colors of the marble slabs (white, pink, yellow marble) are distinguished on a reduced training portion (Fig. 6b). Fig. 6c shows the segmentation results for the altar of Santa Vittoria, annotated based on the type of material.
At a final stage, the supervised classification obtained on the UV map can be projected back in 3D by exploiting the projective relationships between images and model, so to obtain an overall mesh model in which different colors correspond to different degrees of degradation or different types of material [Croce et al. 2022]. Class 6 – Background, related to the plaster of the side wall of the church, could even be used to support the appropriate selection of the mesh faces related to the altar, suitably excluding the faces related to the back wall.
The result obtained via this classification process is a classified datum, both available in 2D and in 3D, in which the portions of materials or the degraded surfaces are more directly recognizable, interpretable and computer-readable. The acquired information can be leveraged to enrich the digital representation with semantic data, related to material and decay mapping.

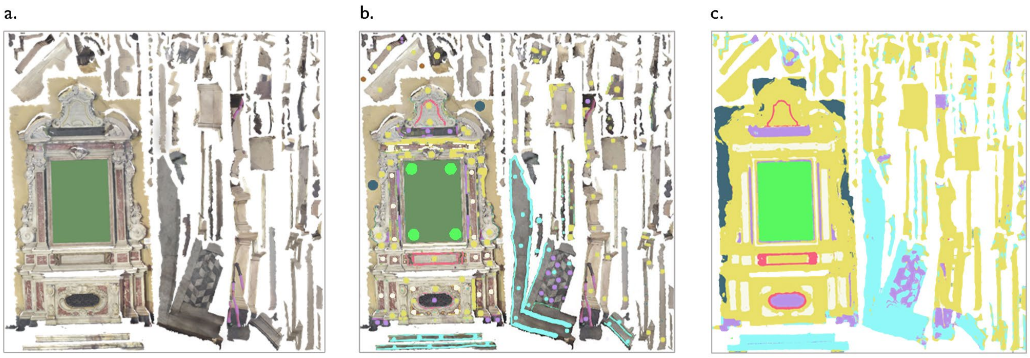

Fig. 6. Altar of Santa Vittoria: UV map (a), training set (b) and segmentation results (c) with related legend.

BIM-Based Reasoning on Material Mapping and Decay Conditions

By exploiting the projective relationships between texture and mesh, the classification information is transferred from the UV map to the 3D model. In a second phase of this work, we focus on ensuring that such a classification information is preserved even when importing the model of the altar or confessional into the BIM environment. To this task, a series of steps are considered relying on the use of McNeel Rhinoceros, Meshlab and Autodesk Revit software, provided as in Fig. 7 for the example of a confessional.

In detail, the classification information is used to duly segment each mesh model based on the color of its texture: in Rhinoceros environment, the color information deriving from the texture is appropriately transferred to the faces of the mesh, by evaluating the color at each texture coordinate (u,v). As such, the color information is transferred from the texture to each mesh face and becomes part of the geometry.

Then, through Meshlab, the initial mesh model is automatically segmented into sub-meshes on the basis of the color of the individual faces that compose it. In so doing, each sub-mesh corresponds to a single class of material or level of degradation, and can be imported singularly within the BIM environment.

To this latter task, the visual programming language Grasshopper, together with the Rhino.Inside.Revit plug-in, is exploited for a more direct connection with the BIM software Autodesk Revit. By a specific algorithm implemented through this plug-in, the architectural objects (sub-meshes) belonging to the single classes of elements are selected and associated to a specific Revit family (e.g., material or decay condition), so preserving their semantic description level (Fig. 8).

The graphical algorithm of Fig. 9, if replicated for each type of material present, thus imports within Revit portions of mesh that can be managed individually, obtained from a supervised classification and belonging to a same family / class.

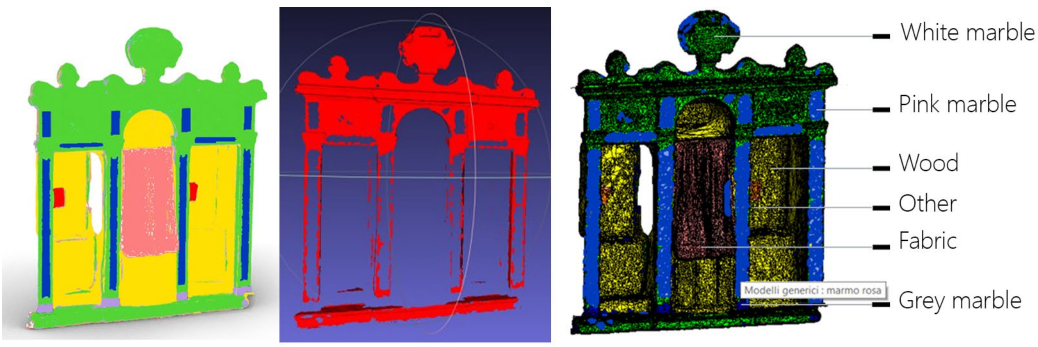

Fig. 7. From annotated data to H-BIM platforms. From left to right: classified mesh model; selection of the mesh relating to a single class; segmented classes visualized in Autodesk Revit.

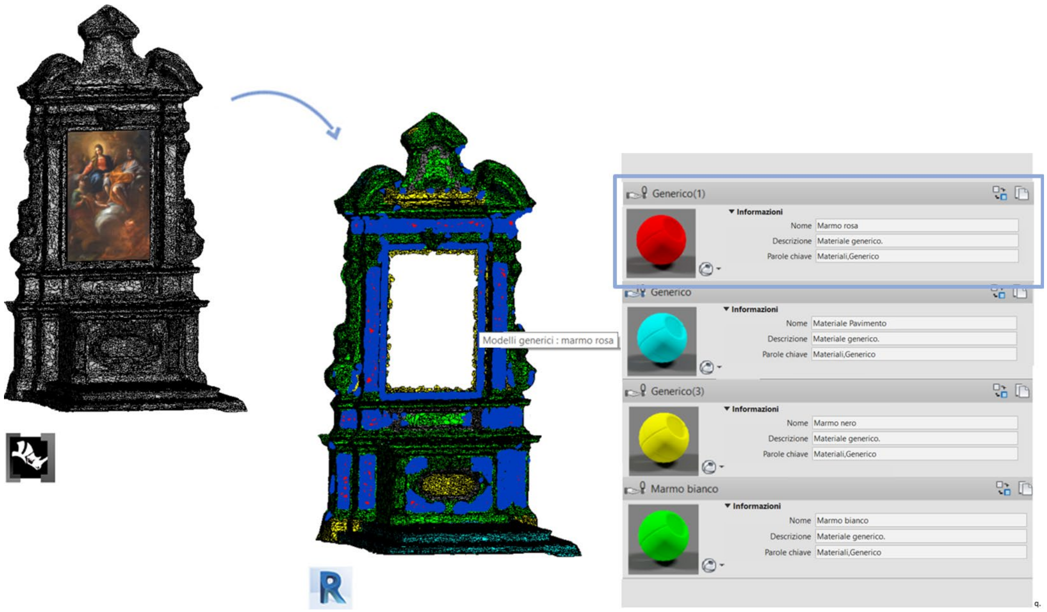

Fig. 8. The mesh is deconstructed according to the identified classes and the related materials are assigned in Autodesk Revit environment by visual scripting.

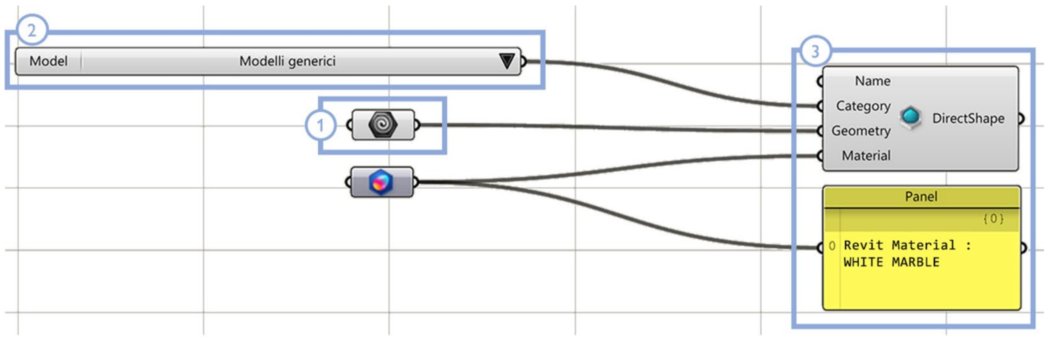

Fig. 9. Exemple of VPL import script via Rhino. Inside. Revit: the selected template geometry (1) is imported in Autodesk Revit as a generic model component (2), and it is associated the Revit Material 'White marble' (3).

In the more general logic of BIM information modelling, the semantic information resulting from the automatic segmentation is so transferred to a 3D information management and sharing environment, such as Autodesk Revit.

Conclusions

The digital representation of complex architectural elements, such as the decorative apparatuses of the churches of the Mendicant orders, may constitute a limitation for the construction of BIM systems for Cultural Heritage. In this context, the 3D model construction and implementation approach proposed in this paper is based on a semi-automatic modelling and classification strategy, exploiting AI and BIM environments. The skillful use of textured mesh models is fundamental in describing the state of surface degradation or the type of material of a certain architectural object, with a more automatic classification method. Therefore, importing single portions of mesh with different material or degradation characteristics into the Autodesk Revit environment guarantees the autonomous management and computerization of the parts composing the digital model. AI represents an extremely effective tool to support the recognition of some distinctive features of the objects, especially relating to the colorimetric and/or geometric nature of the parts. The supervised approach to the automatic classification reduces annotation times and fosters the conversion from survey data to H-BIM models.

As such, semantic data can be more easily shared, retrieved, visualized and stored over digital models, also in view of the use of the latter for augmented reality applications.
The results obtained in terms of description and semantic mapping of the model and of traceability and retrieval of information in H–BIM environment suggest the extension of the proposed methodological approach to the study of ornamental apparatuses related to other churches of the Carmelite order.

Notes

[1] This research is the result of the joint work of six authors. S.T. and V.C. developed the illustrated approach on AI and Scan-to-BIM and conducted the experimental works as part of the M.Sc. thesis by S.T..
V.C. wrote the original draft and prepared with S.T. the paragraph on the case study. G.C, A.P., M.M. and M.G.B. supervised the work and reviewed the paper. All authors shared the analysis of experiments and results.
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[2] The work is part of the large-scale research project 'Seeing Below the Surface: Reconstructing Tramezzo Screens in the Mendicant Churches of Pisa', globally led by Donal Cooper (University of Cambridge, project leader), and locally coordinated by M.G. Bevilacqua and G. Caroti (University of Pisa), L. Repola (Suor Orsola Benincasa) and A. Giordano (University of Padua).

[3] A short video illustrating the contents of the paper is available at the following link: https://youtu.be/CBBd36AuKdc

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