Developing 3D imaging programmes – workflow and quality control

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This paper reports on a successful project for 3D imaging research, digital applications and use of new technologies in the museum. The paper will focus on the development and implementation of a viable workflow for the production of high quality 3D models of museum objects, based on the 3D laser scanning and photogrammetry of selected ancient Egyptian artefacts. The development of a robust protocol for the complete process chain for imaging cultural heritage artefacts, from the acquisition of 2D and/or 3D images to the development of interactive applications for the public audience, was a specific objective of the project. The workflow devised by the university museum team combines reference photography and 3D imaging with a curatorial review of the actual object to its digital counterpart. It also integrates methodologies for managing the accompanying metadata sets to record these activities. As final stage deliverables from the process, the museum is making high quality 3D images of artefacts from its collection available through creation and dissemination of digital 3D multi-platform interactive applications in order to allow remote access and to enhance the Museum's public engagement. The short paper will conclude with practical considerations for a 3D imaging workflow such as time and skills needed, 3D model quality and expectation management.

Categories and Subject Descriptors: [**Computing methodologies**]: Image and video acquisition; , 3D imaging; Mixed / augmented reality; Virtual reality; Image representations, Appearance and texture representations, Camera calibration, Computer vision representations, Reconstruction; **[Software and its engineering]:** Interactive games; Virtual worlds software; **[Information systems]:** Web applications, Users and interactive retrieval; **[Human-centered computing]:** Interactive systems and tools

Additional Key Words and Phrases: Ancient Egypt, museums, 3D imaging.

ACM Reference Format:

Mona Hess, Margaret Serpico, Giancarlo Amati, Ivor Pridden, Tonya Nelson, and Stuart Robson. 2015. Developing 3D imaging programmes – workflow and quality control. *Journal on Computing and Cultural Heritage.* 13 pages.

DOI: http://dx.doi.org/10.1145/0000000.0000000

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DOI:http://dx.doi.org/10.1145/0000000.0000000

1. INTRODUCTION – 3DPETRIE PROJECT AT UCL

As more and more museums begin to explore the potential of creating 3D digital copies of artefacts as a means of increasing public engagement, the need for the development and dissemination of proven protocols for a sustainable, systematic 3D imaging programme within the museum sector has become more essential. The following paragraph shows a brief overview of the context in which the 3DPetrie project was conceived.

The recently published Survey report on Digitisation in European cultural Heritage Institutions 2014 [Stroeker and Vogels 2014] report states that 48% of European collections are 3D 'man-made' material. Therefore, there is a significant relevance and applicability for a well-coordinated fit-for-purpose 3D imaging programme for the remaining roughly half of all 3D objects owned by European museums.

A ground-breaking project for the 3D digitization of cultural heritage was the Digital Michelangelo project [Levoy et al. 2000] for its technical integrated solutions for 3D imaging and use for making the results available to researchers worldwide. Another example is the EU 3D-Coform project ('Tools and expertise for 3D Collection Formation') pursued further developments in free 3D acquisition and processing software, and a distributed repository system for 3D objects [Arnold 2013]. A feasibility study for 3D imaging of museum object of the Victoria & Albert Museum, London, was undertaken within the 3D-Coform project. The need for infrastructure developments, standardized ways of communication, and the design of feasible practical approaches for cultural heritage (CH) professionals was highly stressed by both the EPOCH project [Arnold and Geser 2008] and the 3D-Coform project [Pan et al. 2010]. Recent project go towards mass digitisation of whole collections. The goal of the 3D-ICONS Project is to provide the EUROPEANA database with accurate 3D models of architectural and archaeological monuments via mass digitization driven by a photogrammetric workflow [Guidi et al. 2015], while the 3DCultlab project is creating a prototype for a conveyer belt driven system for large scale digitization [Fraunhofer Institute for Computer Graphics Research IGD 2014]. 3D imaging can be used for heritage institutions in the context of digital documentation, conservation, restoration, interpretation and collection analysis, and an overview of the state-of-the art project has been given by [Pintus et al. 2014].

Within the sector of 3D imaging at heritage institutions for digital documentation and analysis and research, 3DPetrie represents an in-house 3D imaging projects and has been based on a research partnership between The Petrie Museum of Egyptian Archaeology (UCL Museums) and UCL's Department of Civil, Environmental and Geomatic Engineering [3DPetrie team 2014].

The main aims of the project can be summarized as follows:

1. To develop a viable workflow for the production of benchmarked, visually accurate 3D models of museum objects.
2. To enhance public engagement with and access to collections through the development of a range of multi-platform digital interactives, available in the museum spaces or as online apps and resources, and the use of 3D prints.
3. To undertake audience evaluations of the 3D models and digital applications to better understand the impact and the potential of 3D in cultural heritage.

In this project paper we will outline our workflow for the production of 3D models of museum objects, based on colour laser scanning and photogrammetry of selected ancient Egyptian artefacts.

2. WORKFLOW: FROM OBJECT SELECTION TO 'VISUAL SURROGATE'

To meet the objectives outlined above, the project relies on the diverse skills of a core team, in conjunction with a supplemental network of colleagues (see Section 3.4). The workflow was jointly developed between all stakeholders with the aim to create 'visual surrogate' 3D models.

In this context, the 3DPetrie team is defining a 'visual surrogate' as a model which captures the geometry and visible properties of the object to a level where the model is credible as the object within a variety of standard display options; in other words, a model that would be a believable representation whether in a web app, an exhibition, a giant screen or other display modes.

The resulting protocol combines reference photography and 3D imaging with a curatorial comparison using visual inspection of the actual object to its digital counterpart. The workflow is set up in eight sequential phases.

A standardized form (a Process Log) is used to record and track each stage, including information such as the equipment and software used, the processing steps taken, and the comments of the model review. It aims at the thorough documentation of all processes according to [The London Charter Interest Group 2009, paragraph 4.6].

Phase 1: Concept development for 3D imaging

Initially, objects for imaging are selected by the curator, most often in conjunction with a storyline which is to be developed into a digital application. In proposing objects, the curator considers how the story might be delivered and how 3D imaging would help within that context. It is undoubtedly helpful for curators to have a good understanding of the object properties that can present challenges for imaging, for example, high gloss surfaces, translucency and occluded areas.

Phase 2: Object assessment

For each object proposed, the curator starts to fill in a standardized Object Assessment Document (OAD), recording basic information about the object and specifying any features which are especially essential to capture. The OAD is then passed to a conservator who adds a condition report [McKenna and Patsatzi 2009] covering issues such as the suitability of the object for handling and repositioning during imaging, recommended treatment or cleaning and accessibility of the object in storage or display. Guidelines for handling, transport, means of support and environment levels are included. The imaging technician adds comments such as specifying the best technology for 3D imaging, potential problems and projections for the time needed.

Phase 3: 2D acquisition (laser scanning only)

If an object is approved for laser scanning, the whole surface is photographed for reference. A ring-flash is used to avoid shadows and the digital photographs are colour-corrected and used for cross-comparison quality checking during the subsequent 3D modelling process. While, ideally, the modelling of the 3D object would be done with the object available for reference, in practice this is not always possible. Moreover, because the photographs can be archived, they are a referenced indication of the colour and lighting conditions used to create the model. The photographs are similarly available to the curator as part of the quality control procedure.

Phase 4: 3D acquisition

The 3D imaging of an object is then carried out using the most appropriate of the three available types of acquisition for primary and 'raw' data: 3D colour laser scanning as active 3D imaging method; photogrammetry (multi-view stereo) and Structure from Motion (SfM) as passive 3D imaging method.

UCL has been in a collaborative partnership with Arius3D (2006 to 2013) which included the loan of two state-of-the-art colour 3D laser scanners. Therefore, the 3D colour laser scanning was used to produce a coloured 3D pointcloud of the object surface with a maximum sampling interval of 0.1mm (100 micrometres or ~250 dots per inch) over the surface of an object [Foundation Model 150, Arius Technology 2014]. Measurement uncertainty of the sensor is +/-0.035mm in depth (z-axis) and of the order of +/-0.1mm in x- and y-axes due to planimetric point spacing and laser spot size. The planimetric uncertainty dominates the geometric alignment with the result that the accumulated error is of the order of ±0.1 mm in all three axes. Surface detail can therefore be recorded with 0.2 mm or larger, i.e. twice the sampling distance. The scanner collects 3D geometry information through the use of a laser triangulation system, whilst colour is simultaneously collected by analysis of the reflected light from three RGB lasers with the wavelengths of 473/445, 532, 638 nanometers [Hess and Robson 2010]. This methodology was ideal to document objects of the size from ca 1cm to 30cm. For all recorded objects the highest obtainable resolution in the acquisition stage was used.

For this 3D imaging project the high-quality geometry and colour recording capabilities of the AriusTechnology 3D colour laser scanner were available, but 3D acquisition can also be delivered by commercially available and often less costly devices, such a s structured light scanning or handheld laser scanning, combined if necessary with texture mapping of colour information onto the 3D shape.

For larger and more fragile objects, such as Egyptian cartonnage masks about 70cm long and 50cm wide, dense stereo matching and photogrammetry has been used. The MVS (multi-view stereo) photogrammetry method has been described in detail in [Hosseininaveh Ahmadabadian et al. 2012], Figure 2. After geometrically correcting the images (known as image undistortion), corresponding image measurements were extracted from the network and used to compute approximate 3D coordinates in Bundler [Snavely et al. 2008]. A photogrammetric network adjustment, using the relative orientation parameters of the stereo camera as geometric constraints was then computed to estimate the length of the stereo baseline within the network. This length was compared with the calibrated baseline to estimate a scale factor, which was then applied to the camera locations and 3D coordinates. After resolving the scale, this data was input into PMVS processing software to generate a dense pointcloud [Hosseininaveh Ahmadabadian et al. 2013].

The project is also using photography-based 'Structure from Motion' with a variety of freeware and commercial software (Figure 3). Structure from Motion (SfM) was used in the museum photographic lab, with the advantages of not needing to transport the object and for recording high-resolution, high-fidelity texture colour values. The method is increasingly used in heritage imaging and archaeology and uses the principle that movement through a scene allows an understanding of the shape of the scene in three dimensions, in the same way as walking through a room allows one to visualise the space and objects placed within it. In SfM this is represented by a series of systematic viewpoints; overlapping photographs taken from different angles around the object. The recording principle is single image photogrammetry and the reconstruction of the 3D model uses the same steps of a photogrammetric workflow with: image recording, orientation through image point measurement and bundle adjustment, measurement and analysis based on internal and external geometry. The processing includes colour calibration, image masking, with an output of a coloured pointcloud or coloured polygon mesh. The 3D model is reconstructed by using PMVS/CMVS and Bundler as free software. Both methods deliver as outcomes a 3D polygon model with an uncertainty to the order of 0.2 mm lateral (spatial) and depth (structural) resolution, either with texture or colour per vertex.

Figure 1. 3D acquisition with 3D colour laser scanning

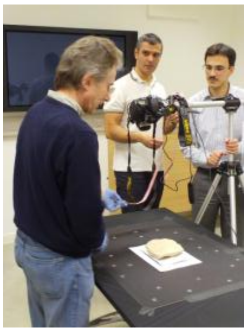

Figure 2. 3D acquisition with multi-view stereo photogrammetry

Figure 3. 3D acquisition with single image digital photogrammetry

To maintain all information of the 3D image production, the Process Log was kept containing the following metadata information: operator, recording technology, previous calibration results and expected uncertainty, and steps to perform 3D imaging procedure (e.g. records from different directions). Control measurements with a colour chart are stored alongside the raw data.

Phase 5: Processing

The 3D model is built up by aligning and adjusting individual scans taken at different angles, or by creating a surface model from photographs. This first phase of modelling is the production of an ‘as-recorded’ archival 3D model, with no further digital changes than cleaning the point cloud or assembling the surface model. The metadata set for the processed model includes information about alignment results (RMS values).

Archiving of the processed model is essential in case post-processing steps should need to be repeated, or different processing methodologies come to the market. The archived model is also potentially important for any object-based research because it represents the most faithful data captured.

Phase 6: Post-processing

The next phase includes further 3D modelling steps, such as hole-filling, complementing any missing geometry by 3D modelling, and adjusting the colour to match the reference photography. Great care has been taken to obtain the most faithful colour on the 3D model for both 3D colour laser scanning and photogrammetric methods, when viewed on a colour-calibrated screen.

The following steps have been followed for 3D colour laser scanning: a colour chart (x-Rite Passport) has been photographed in the same lighting conditions as the artefact with all reference photography datasets (Phase 2); subsequently a colour profile was created which was applied to correct the colour values of the reference photography.

Furthermore a monitor profile could be imported into the proprietary software (Poinstream) and additionally the display monitor was colour calibrated. Manual adjustment were undertaken in the colour menu of the software (R,G,B sliders) to adjust the colour values to produce the closest possible hues to the reference photography on the same screen. These applied values were documented in the metadata log. The post-processed model can be used to derive any further models (for example for phase 8). The project has shown that about 40% of the time to produce a 'visual surrogate' is spent on post-processing.

The metadata log, also called 'digital provenance' information, for phase 6 include the textual documentation and archiving of 3D models of necessary processing steps, to separate out procedures based on mathematical processes from any follow on steps that involve human decision making.

Phase 7: Quality control

The project curator then conducts a review of the post-processed model, cross-checking the quality against the actual object, the earlier processed model, and (if appropriate) the 2D reference photographs. The Petrie Museum is closed one day per week, so any object movement out of storage spaces and display cases and 3D model review was preferably done on this day. For Quality control, the actual object needs to be viewed under a daylight lamp set up next to a colour calibrated (mono) screen. Any discrepancies between the object and the model, such as inconsistencies in colour, specularity, resolution, hole fills, layer blending, etc., were recorded into the Process log and reported back to the 3D modelling technician in word and image (screenshots). Multiple iterations of post-processing and review may then be necessary to improve the quality of the 3D model until the 'visual surrogate' level is reached.

While the quantitative, metrically correct 3D surface recording can be controlled and verified numerically, and has been ensured in this project, the Quality Control is a qualitative procedure relying on the subjective visual perception and visual acuity of the reviewer, who has been trained in the use of 3D imaging software to inspect the 3D model. Consistent high-quality output of 3D models with high visual quality showed that visual inspection skills can be transferred the virtual 3D realm, to 3D images on screen.

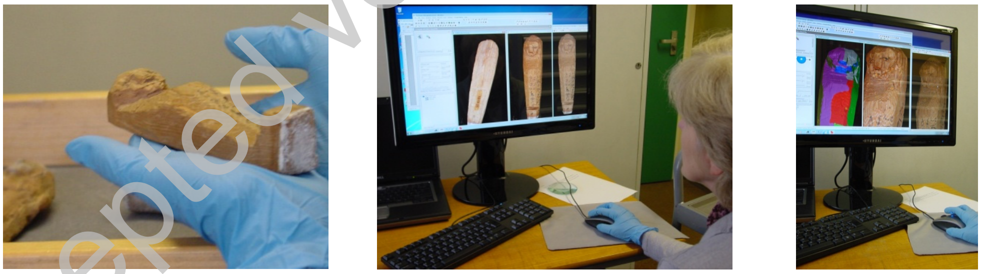

Figure 4 Quality control to reach 'visual surrogate level' a) by crosschecking the 3D model against the real object, b) by comparing different modelling phases and c) and by verifying cleaning steps and best representation of key features in in the post-processed model.

Phase 8: Digital outputs/ interactives.

As a final stage deliverable of the process, the museum has created a variety of digital multi-platform interactive applications using 3D images its artefacts. As well as stand-alone interactives, digital outputs and 3D prints can also form part of larger exhibitions, such as the current Petrie exhibition at UCL Qatar.

As the focus of this paper is on the imaging protocol, the workflow for the resulting digital outputs will be briefly summarized. First, a storyline brief was developed in full, taking into account the digital assets needed (e.g. 2D, 3D, audio/visual), and graphic and user interactivity design. The concept design also considers the target platform (e.g. PC, webpages, iOS and/or Android handheld devices), as well as the various technologies to be integrated (Augmented Reality, gesture tracking, Oculus Rift, Google glasses, etc.).

With regard to the 3D models included in the interactives, the aim has been to enable easy access and engagement while maintaining a high-quality visual standard. This typically requires further processing of 3D images, including transfer from a high-quality coloured point cloud to a decimated polygon mesh (i.e. surface) model. Some platforms limit the amount of triangles, therefore a maximum number of polygons have been assigned whilst maintaining a maximum curvature and edge quality for the polygon decimation computation. For interactive web display, and taking into account a household with average bandwidth, the following steps need to be implemented: reduction of the surface geometry to a low polygon count to decrease the file size as described above, application of a normal map, bump map and re-projection of the high-resolution texture map from the earlier higher resolution polygon model, to create a photo-realistic rendering of the coloured 3D model [Amati 2014].

At this stage, the resulting file is not only applicable for interactives but can also be sent out for 3D colour printing (3DPetrie 2014).

For delivering the concept design, Unity3D [Unity 2012] was one of the design frameworks used in the development of some of the interactives, such as the Tour of the Nile iPad app, programmed in C#. Another example of a digital output is the recently launched 3DPetrie interactive website (Figure 5) which is based on a WebGL API (Three.js), where the models can be viewed interactively [3DPetrie 2014].

To inform current and future development, user-testing sessions, as well as formative and summative evaluations of the digital resources, have been carried out and assessed.

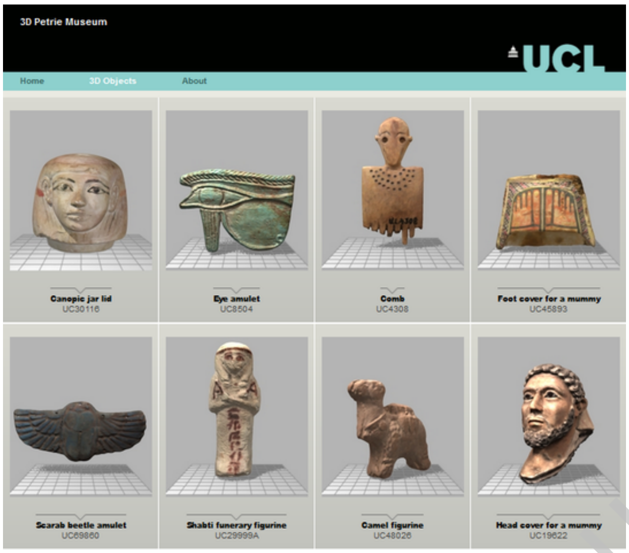

Figure 5. 3D image library of The Petrie Museum created by the 3DPetrie project.

3. PRACTICAL CONSIDERATIONS FOR AN IMAGING WORKFLOW

3.1 Expectation management and model quality

A prerequisite of the development of a 3D imaging programme is regular dialogue and early agreement on a strategy between all stakeholders of the project to ensure the resulting models are fit for purpose. As 3D imaging and 3D printing currently have a high profile in cultural heritage, expectations for easy and quick achievement of virtual surrogates and high-quality 3D printing may be set unrealistically high.

In creating visual surrogates, the important criteria to agree are the colourimetric and geometric accuracy, and the degree of detail or the smallest feature to be recorded and displayed. It is important that all stakeholders define their expectations for these, balancing available resources with the recognition that different outputs may affect controllability. While geometric recording capabilities of 3D imaging systems can be quantified with engineering metrology methods [Hess et al. 2014], subject specialist curatorial input is especially important to ensure that the model is an accurate visual representation. But it should be remembered that 3D model quality is currently a subjective issue and dependent on the observer and the viewing environment.

3.2 Integrating workflows

3D imaging programmes can be disruptive to the regular workflow of the museum. It is important to resolve any problems that can arise in coordinating access to objects, space, equipment and other resources.

3.3 Production time

The production time for a 3D visual surrogate is relevant for the planning and for the sustainability of a 3D imaging programme. Production times for structured light scanning and the relation between acquisition (3D imaging) time and processing time were reported in [Santos et al. 2014, fig.1]. Time for processing can also be split up in pure ‘computer time’ (automation or computations without an operator) and interactive ‘person time' [Mathys et al. 2013].

Additionally, operator skills greatly influence 3D measurement time employed and 3D results. Specialist knowledge of use of these sensors is acquired by practice, which will yield good 3D image quality as a result in a shorter time. There is clearly a learning curve involved in gaining the necessary mechanical and digital aptitudes for using measurement tools. The time relationship between 3D recording activity and subsequent processing needs to be taken into account, as it is usually 1:3 up to 1:10 for 3D image production in the 3DPetrie project. It was found that the time employed varies for each object with differences in properties such as object surface complexity, details of surface geometry and colour, and gloss. Likewise it varies the time to produce a visual surrogate varies for different methodologies and processing strategies. Details for a representative 3D model produced with 3D colour laser scanning are shown in Table 1 and Figure 5.

Processing steps	Object Egyptian shabti UC 29999A (in hours)
Overall Admin time/ Metadata record	1 hrs 15 mins
2) Object Assessment Document	4 hrs
3) 2D acquisition + processing (colour profile etc)	2 hrs
4) 3D acquisition with 3D colour laser scanning and scan log writing	7 hrs 10 mins
5) + 6) Processing work (Technician)	8 hrs 45 mins
7) Total for Quality Control prior to curatorial review (Senior Technician)	45 mins
7) Total for Curatorial review model (Digital Curator)	2 hrs 12 mins
TOTAL time	26 hrs 12mins

Table 1: Time involved for the production of a 3D visual surrogate from Egyptian shabti (accession number UC 29999A, UCL Petrie Museum)

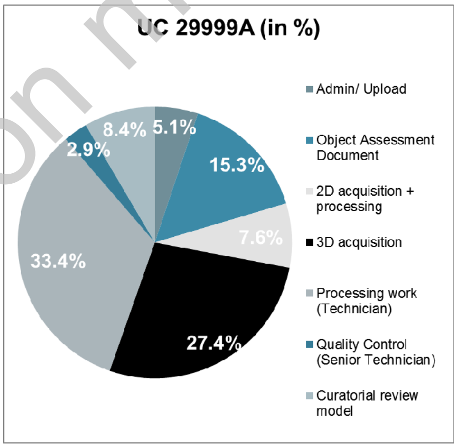

Figure 6. Time involved for the production of a 3D visual surrogate.

3.4 Skills needed

To replicate the workflow outlined here, a range of skills is necessary. For the 3D imaging stages, the skills needed would be: 1) 3D imaging specialist for each technology used; 2) 3D modeling specialist; 3) a 2D imaging specialist, 4) subject specialist curator, and 5) conservator. For the interactive outputs in the workflow, the skills needed would be: 1) software developer, 2) user interface designer, 3) graphic designer, and 4) subject specialist curator. The project overall should also have a project manager/administrator. Whether the skills are available in-house or would need to be outsourced would depend on the circumstances of the individual museums. In practice, members of the 3D Petrie team were able to cover multiple skills. For example, one of the 3D imaging specialists was also a trained conservator.

It is also worth bearing in mind that the required skillsets may need to be reconsidered in the future as more advanced imaging technologies and image processing software applications are developed [Robson et al. 2012].

3.5 Costs involved

The expense of setting up a successful 3D imaging project should not be underestimated. There is a broad range of costs for imaging equipment but these choices must be matched to the level of quality necessary. Equipment loans might be an alternative, but maintenance of all equipment should be taken into account. Similarly, the purchase of other hardware and software, as well as appropriate licenses needs to be factored. As well as staff costs, dedicated time needs to be allocated to train staff, keeping in mind the learning curve necessary to reach an efficient level of production. Furthermore, provision needs to be made for a suitable environmentally-controlled space for imaging, such as a professional studio.

3.6 Sustainability and data management

The continuity of technical expertise and maintenance of software and hardware can be very challenging. Moreover, standardized protocols for the archiving and digital preservation of all data associated with a 3D imaging project have yet to be fully resolved. Data storage can be secured by server-based redundant storage, but protocols for integrating this data into museum management database systems are still problematic. Some projects, such as 3DCoform, have made first steps in the direction of a 3D data repository and exchange platform [Arnold 2013].

4. CONTRIBUTION AND BENEFIT

The 3DPetrie imaging programme has resulted in the development of a library of 3D models which have also been used in a variety of digital outputs. The public response to the developed resources has been resoundingly positive [Serpico et al. 2013] and the project has significantly increased actual and remote visits to the museum. An integrated communication and evaluation process to ensure 3D image quality has been established between the imaging technician and heritage professional. It is hoped that dissemination of the workflow protocol, as well as the intended dissemination of the data management methodology, will encourage the digitisation and increased accessibility of other collections.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Arius Technology, IET and 3DEncounters.

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