The 12th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2011)
M. Dellepiane, F. Niccolucci, S. Pena Serna, H. Rushmeier, and L. Van Gool (Editors)

A Methodology for the Physically Accurate Visualisation of Roman Polychrome Statuary

G. Beale[1] and G. Earl[1]

[1]Archaeological Computing Research Group, University of Southampton, UK

Abstract

This paper describes the design and implementation of a methodology for the visualisation and hypothetical virtual reconstruction of Roman polychrome statuary for research purposes. The methodology is intended as an attempt to move beyond visualisations which are simply believable towards a more physically accurate approach. Accurate representations of polychrome statuary have great potential utility both as a means of illustrating existing interpretations and as a means of testing and revising developing hypotheses. The goal of this methodology is to propose a pipeline which incorporates a high degree of physical accuracy whilst also being practically applicable in a conventional archaeological research setting. The methodology is designed to allow the accurate visualisation of surviving objects and colourants as well as providing reliable methods for the hypothetical reconstruction of elements which no longer survive. The process proposed here is intended to limit the need for specialist recording equipment, utilising existing data and those data which can be collected using widely available technology. It is at present being implemented as part of the "Statues in Context" project at Herculaneum and will be demonstrated here using the case study of a small area of the head of a painted female statue discovered at Herculaneum in 2006.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism

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1. Introduction

The *Statues in Context* project, was first conceived when, in 2006, the head of a statue of a young woman was discovered in the area of the Basilica Noniana at Herculaneum [GG08]. The statue was virtually unique in the extent to which the paint survived upon its surface. This statue served as a vivid reminder that far from being uniformly white, as had been widely accepted, Roman statuary would very often have been brightly coloured and adorned with various decorative elements. As well as these applied colours a wide range of materials, each with unique colouristic properties, were used in statue production, from dark bronzes through to the subtly differing tones of white sculptural marble. In short, the Roman statue was an extremely complex and inherently coloured object.

As a consequence of this discovery it became clear that further research into methods of studying Roman polychrome statuary, particularly visualisation techniques might be fruitful. A collaborative project was initiated, the purpose of which was to further develop understandings and knowledge of polychrome statuary. One of the core functions of this project was to provide a means of visualising and visually engaging with the statuary. These visualisations were intended to act not merely as illustrations but as tools for collaborative visual engagement to which participants could respond and through which interpretations could be shared and explored.

The methodology proposed here relies, to as great an extent as possible, upon tools and data which are widely available or easy to acquire within a conventional archaeological research setting.

Figure 1: *The case study: A statue of a young woman from Herculaneum, Italy.*

In this way it is hoped that the methodology can, with a small amount of modification according to the resources available, be easily applied elsewhere without the need for specialist equipment or dedicated computer graphics expertise.

DOI: 10.2312/VAST/VAST11/137-144

The work presented here revolves around the production of a visualisation of the artefact as it exists today. Clearly there is potential for hypothetical virtual reconstruction of the statue; both geometrically and in terms of colour and surface. While these possibilities are not explored here it should be noted that the requisite data, those relating to experimentally reproduced pigment have now been made available by this phase of the project. The possibilities of this next phase of research will be developed upon in section 6 of this paper.

1.2. Objectives

The methodology was required to be:

- Physically Accurate: The accuracy of the simulation was paramount. The resulting images were to be used as interpretive tools and as such were required to represent a reliable simulation of real world phenomena. A complete predictive rendering pipeline would not be appropriate at this stage of the project due to the requirements of flexibility and efficiency outlined below. However many of the methods and data required to implement a methodology of this type have been integrated and will be utilised for this purpose at a later stage. These developments are described at greater length in section 6.

- Flexible: Necessity dictated that the methodology be sufficiently flexible that it could encompass fragmentary data sets whilst remaining robust. This flexibility would allow the methodology to be applied in the widest possible range of circumstances and would allow the creation of images which would vary in type from conceptually simple visualisations of surviving material through to experimental and almost completely hypothetical reconstructions.

- Sustainable: The proliferation of technologies which allow the production of physically accurate computer graphics have brought the necessary technologies into the hands of many archaeologists. The methodology proposed has been designed to ensure that these tools are used appropriately and that the processes involved are as intuitive and reflect conventional archaeological practice to as great an extent as possible.

- Efficient: it was crucial that the production process was efficient, allowing the high speed production and modification of visualisations in relation to ongoing interpretive discourse.

2. The Painted Statue

The case study used here to explain the methodology was chosen due to the fact that within this small area the majority of the phenomena that characterise the appearance of many Roman painted statues are evident.

Statue marble generally features subtle changes in colour, surface texture, translucency and glossiness. Often layers of applied colour must also be taken into account resulting in a complex interplay of translucent materials which is challenging to represent using conventional computer graphics approaches.

It remains uncertain exactly how these complex reflective behaviours might have been manipulated in antiquity in order to create specific visual effects. However many examples, including the subject presented here, are sufficiently well preserved that they do have the potential to allow us to observe the effects which were achieved and so to begin to hypothesise as to the nature of the visual effects which were possible [B07]. In this way, physically accurate virtual reconstruction may offer a very valuable supplement to traditional forms of analysis and representation.

Figure 2: *A close-up photograph of the eyes with noticeable subsurface scattering.*

Within the sample area four separate areas of pigment (illustrated in Figure 3) have been identified. Identification of the colourants present in these areas have not been finalised, however they have been provisionally identified as being likely to be iron oxide based pigments such as ochre or haematite. This hypothesis is based upon visual inspection and upon comparison to data collected from other correlating statues using multi spectral imaging, visible induced luminescence, x-ray florescence and microscopy [Ø10]. The binding media of these pigments has been analysed and has identified as egg yolk [T07]. The paint in the sample area is remarkably well preserved and clearly defined.

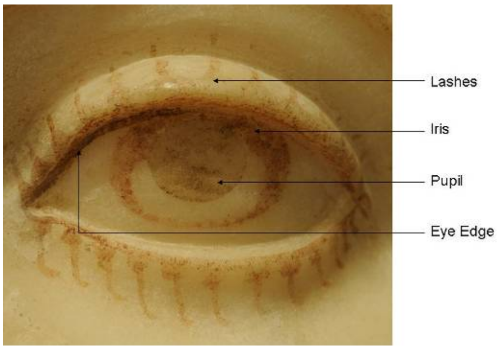

Figure 3: *The painted areas can be seen in this close up photograph of the study area.*

The stone itself is noticeably translucent. An incidence of this phenomenon is highlighted in figure 2. While, of course, this effect is most notable on thinner areas of the statue, it characterises the visual appearance across the surface. Due to the characteristics of the marbles used this phenomenon is a ubiquitous feature of Greek and Roman marble statuary and must be taken into account within the simulation.

The result of this combination of materials is that the sample area exhibits complex reflective characteristics with a translucent base material overlaid with thin layers of pigment. The simulation of such a surface would until very recently have been extremely challenging, especially outside of the context of computer graphics research. However, recent advances in commercially available recording, modelling and rendering solutions have brought techniques such as multi-layered subsurface scattering and physically accurate lighting simulation into the realm of applied research.

3. Related Work

The intention to produce physically accurate computer graphics which offer a correct, rather than a *believable* representation of light behaviour within a virtual scene sits at the heart of this project. These ideas are explored at length by Wilkie, Weidlich et al. in their 2009 SIGGRAPH Asia course on *Predictive Rendering* [WWM*09]. Their paper provides a comprehensive review of the steps necessary to formulate a methodology which accurately captures, simulates and represents real world phenomena.

While very few archaeological projects have fully implemented a predictive rendering pipeline, there have been several which have drawn upon certain aspects of physical accuracy in order to address specific archaeological research questions, [EBH*09; GSM*04; SCM04; F06; GCL06; GSG*08; HWT09]. Of particular relevance to this project has been Chalmers' research into *authentic illumination* and the production of archaeological visualisations which incorporate physically accurate simulation and hypothetical data [CRL06].

The value of a physically accurate rendering approach lays primarily in the possibility offered by these techniques to experiment with hypothetical variables within a controlled and reliable virtual environment. There have been several extremely successful attempts to produce physical reconstructions of Greek and Roman polychrome statuary [Ø10; B07]. However, the level of resources needed to produce physical replicas has meant that relatively few are produced at any one time. Consequently opportunities to use the practice as a means of exploring a large range of hypothetical alternative interpretations of a single object have been limited. The physical accuracy of the methods described here coupled with the relative ease with which they can be produced and altered means that they have great potential utility as research tools, especially where used in conjunction with aspects of physical reconstruction.

Specific developments in physically accurate computer graphics research have enabled this research to take place. Perhaps most significant have been the development and increased availability of unbiased rendering and the expansion of more efficient biased rendering solutions to include physical subsurface scattering.

The implementation of unbiased rendering techniques like path tracing within commercially available software greatly enhanced the potential for demonstrable accuracy in archaeological visualisation [K86; HH10]. Renders produced using these techniques can be used to produce reference images against which images produced using more efficient, biased techniques such as photon mapping can be compared [KWB09].

Subsurface scattering was an essential consideration when deciding how best to simulate the appearance of statuary. As mentioned above, many, if not all, of the materials which were used in statue production are to some extent translucent. This complexity is compounded by the fact that these materials are also layered. Many of the earliest attempts at simulating subsurface scattering focussed upon homogenous materials such as milk, marble or skin [HK93; JML*01; JB02]. However, the advent of multi-layered subsurface scattering allowed non heterogeneous materials to be simulated with a much higher degree of accuracy [GLL04; PBM06; A09; DWP10]. The implementation of multi layered subsurface scattering within commercially available renderers such as Mental Ray, Maxell, Renderman, V-ray and the open source Blender has broadened access to rendering with subsurface scattering and has placed this technique within the grasp of non-expert users, greatly increasing the potential utility of these techniques as archaeological tools [STH*03].

4. Methodology

4.1. Rendering

The primary renderer for this project has been mental ray as implemented within 3ds Max. Photon mapping was used in all renders featured in this paper. A biased rendering solution was selected for reasons of efficiency consequently a process of verification was undertaken in order to establish the difference between specific pixel values in the render to those produced using an unbiased path tracing renderer. iray, a path tracing renderer implemented within 3ds Max will also be used in order to produce reference images against which the ray traced renders can be compared and verified [M11].

4.2. Data Acquisition

Geometry: The geometry featured in this case study were captured using a Metris laser scanner. This system is capable of recording 80,000 points per second at a resolution of between 0.05mm and 0.06mm. In the absence of specialist equipment geometry could be represented using photogrammetric techniques. The resolution and size of the mesh used for this methodology is limited only by the computational resources available to process the data. Extremely high resolution geometric data sets could be employed if it were a requirement of the methodology to do so. Subsequent stages of the project will make use of higher resolution meshes in order to ensure a higher degree of physical accuracy in the visual output. The need for this, as well as other features necessary in order to implement a predictive rendering pipeline are discussed in section 6.

Surface: A number of techniques were used to gather data relating to the surface properties of the subject. The majority of necessary data were collected directly from the surface of the statue. Other data which could not be collected directly from the statue were collected from an experimentally repainted sample of Pentelic marble of the type used to produce the statue. This sample had the benefit of being portable and could be subjected to analyses which would not be possible using the statue. The specific uses to which these data were put is described at length below in section 4.3. Data collected in this way would also inform the hypothetical reconstruction of the virtual statue, allowing a meaningful estimate to be made of those variables for which data no longer survives.

Colour data were collected from colour calibrated images of the statue. Images were taken with a Nikon D3x at a resolution of 24mp, allowing small fragments of pigment to be identified and the colour measured accordingly.

In order to asses the influence of light position and viewer position upon the visual properties of the statue it was necessary to capture Reflectance Transformation Imaging data from a number of angles and to compare these data to rendered geometry [EBM*10]. The fragility of the statue meant that whilst RTI data were captured from the statue, the majority of these measurements (including those used below) were captured from the marble sample. RTI captures were taken from several directions in order to establish the effect of viewer position upon colour. These comparisons allow colour to be precisely identified according to visual characteristics and allow an estimate of the reflective characteristics of the surface to be achieved. These data are insufficient to allow BRDF and/ or BSSRDF models to be defined but they enable estimated modifications to be made to existing models. This allowed an approximation of the surface characteristics of the painted and the unpainted areas to be made. The process by which these approximations were implemented will be described below in section 4.3.

Appropriate subsurface scattering characteristics have been based upon absorption and scattering co-efficients captured by Jensen et al. [JML*01] relating to a generic marble material. These values can, where necessary, be revised appropriately following the verification process outlined in section 5.

Light: The images of the subject, against which the rendered outputs will ultimately be judged were lit using high dynamic range environment maps captured at the same time that the subject was photographed. Photographs of the painted marble sample were taken under controlled lighting conditions using a 75w incandescent bulb of known properties allowing the virtual scene to be straight forwardly lit in the same way.

4.3. Modelling Materials

Marble: The marble material was based upon the physically accurate subsurface scattering shader distributed with mental ray. The shader allows the reflective characteristics of the material (including absorption and scattering co-efficients) to be manually defined according to the values stated by Jensen et al. [JML*01]. These values were tested as described in the verification experiment described in section 5 and the data were found to be a good match. The diffuse colour values for the marble material were defined according to the process described above. These were distributed using procedural maps manually designed to resemble the appropriate distribution of colour across the surface. The veining and natural structure of the marble also allowed the internal variance in colour to be estimated.

Pigmented areas: The painted areas were coloured according to the data collected from the statue as described in section 4.2. Extremely high resolution photographs of the statue were colour calibrated using colour checking charts contained within the images. The colour values were distributed across the surface of the statue using layered distribution maps derived from the photographic record of the subject. A monochrome map was created for each pigmented area, these were then over-layed onto the underlying marble material. The layering of the paint over the surface of the marble material was achieved by manually defining the layering characteristics of the subsurface scattering shader. The transparency of the top layer of the subsurface scattering material was defined using a photographic map allowing the underlying marble material to show through where necessary. The index of refraction of the painted areas could be altered independently but was estimated and judged (based upon the RTI experiments outlined in section 4.2) to be similar to that of the underlying marble surface. Layer thickness was measured from the painted marble sample and was found to be uniformly <0.1mm.

Verification: Verification of rendered outputs has been a key feature of this methodology due to the fact that it is able to provide confirmation of the accuracy and integrity of the simulation process. This allows the methodology to incorporate a variety of data whilst maintaining a demonstrable level of accuracy. The majority of the verification processes described here involve image comparison, this ensured that the inspection process was accessible and comprehensible to both archaeological computing specialists and those with conventional archaeological research backgrounds. Verification was employed at several stages during the methodology. There will be two phases, the primary phase of verification will be used in order to modify or to refine the simulation. The secondary phase will take place after the production of output images in order to confirm the accuracy of the simulation.

Phase 1) Very few archaeologists have access to the equipment necessary to acquire data needed to manually define the volumetric behaviour of light within a translucent object. Consequently this methodology proposes the use of generic subsurface scattering data which are widely published and can be modified in order to produce a good estimate of the subsurface behaviour of the material in question.

A sample of Pentelic marble of a type very similar to that used to produce the subject statue was illuminated using a controlled light source (a 75W incandescent bulb) shining through a circular aperture of 5mm diameter. No other light was admitted. This scene was then precisely reproduced in virtual space, the resultant images could then be subtracted from one another. The output image represents the degree of inaccuracy which can either be tolerated or the settings modified accordingly and the process repeated according to the level of accuracy required.

Phase 2) The second process of verification was undertaken in order to establish the difference between those renders being produced using ray tracing with photon mapping and those produced using an unbiased path tracing renderer. Verification was also employed in order to ensure that data which were not taken directly from the subject were appropriate and behaving correctly.

A test image of the marble sample produced using mental ray was verified against an equivalent produced using iray, a path tracing renderer, in order to ensure that no appreciable loss of accuracy took place due to the use of a biased renderer. Once the integrity of the simulation had been confirmed further images could be produced using mental ray. The two images were compared by subtracting one from the other, the significance of this difference can then be assessed. The results of the comparison for the case study can be seen in figure 5.

Output images were also verified against data collected from the subject. Unlike the previous process which used image subtraction in order to establish difference the comparison between the source data and the output image will be based upon colour values at identifiable points of the image. This is a necessity due to the difficulty of producing a rendered image with a pixel to pixel match to a photograph. The comparison is sufficient though to ensure that no significant alteration of colour has taken place between the original data and the output image.

4.4. Display

The use of calibrated displays is of central importance to a physically accurate image synthesis pipeline. A display must be calibrated in order to ensure the optimal representation of the colour space being used. A single calibrated display was used in order to ensure a consistent approach to the modelling and verification process. However, it was not possible to ensure that all displays upon which the images were seen (as they were disseminated and discussed) were calibrated in the same way. Images were viewed on a range of devices including CRT monitors, led displays and ipads as they were disseminated amongst project partners. This compromise in accuracy was necessary in order to ensure that the images were actively employed as part of the interpretive process were and not seen as obstructive or difficult to use. Solutions to this problem will be investigated as research continues.

5. Results

5.1. Verification

The use of verification as a technique of ensuring the accuracy of the simulation was extremely successful. The images produced for quantitative comparison also allowed a simple visual inspection of the accuracy of the simulation to be made by all of the researchers involved in the project. Consequently the verification process had the twin benefits of ensuring the accuracy of the simulation and also communicating the significance and reliability to researchers without an expertise in computing. A visual impression of the success of the experiment can be gained from figure 6; a photograph of the statue (left) is presented next to a render produced using the pipeline described here (centre), next to both of these is an image produced previous to this work being undertaken (right). The latter image has been produced based upon a visual inspection of uncalibrated photographic data and without subsurface scattering. The lighting in the two renders is identical.

Subsurface Scattering: As mentioned above, the subsurface scattering marble material was based upon the absorption and scattering co-efficient data collected by Jensen et al.[JML*01]. Verification of these data was necessary due to the variable properties of different marble types. The difference between the rendered result and the photograph of the marble was negligible. The values represented a sufficiently accurate description of the subsurface scattering properties of the pentelic marble sample.

Colour: As mentioned above, colour values were taken from calibrated photographs of the statue. The impact of viewer position and light position was established through the comparison of RTI captures of the painted marble sample. Summarised results of this comparison are presented below in table 1. As this table demonstrates, the variation according to light position and viewer position is very slight.

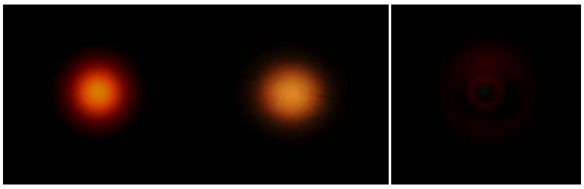

Figure 4: *Left, simulated subsurface scattering penetrating the virtual marble sample. Centre: photograph of light penetrating the marble sample. Right: The difference between the two images.*

Simulation Verification: A test scene including the painted marble sample was rendered using path tracing, a separate, identical image was rendered using ray tracing combined with photon mapping. The first image was then subtracted from the second. The results of this can be seen in figure 4. The difference between the images was very slight and concentrated primarily around the influence of fine surface details.

	Light Position 1					
	Rendered Image			Photograph		
	R	G	B	R	G	B
Light Red Ochre	188	118	48	255	158	45
Medium Red Ochre	243	167	89	250	165	78
Haemetite	248	177	100	254	174	75
	Light Position 2					
	Rendered Image			Photograph		
	R	G	B	R	G	B
Light Red Ochre	255	168	65	253	131	22
Medium Red Ochre	255	181	95	255	164	50
Haemetite	255	183	100	255	172	70

Table 1: *Showing a comparison between colour values in photographs and rendered images from two different light positions, 0 degrees and 45 degrees.*

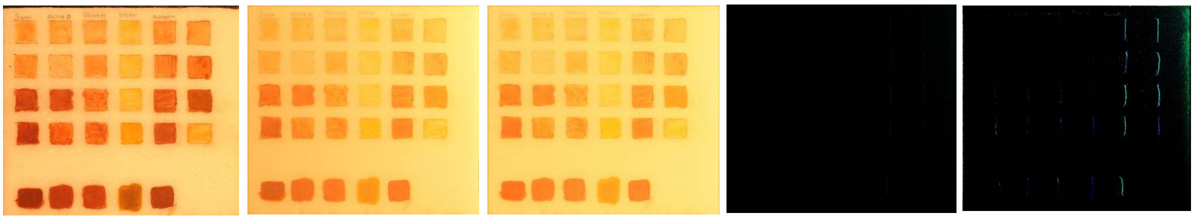

Figure 5: *From Left, a photograph; an image rendered with path tracing; an image rendered with ray tracing; the difference between the two rendered images; the difference between the images squared.*

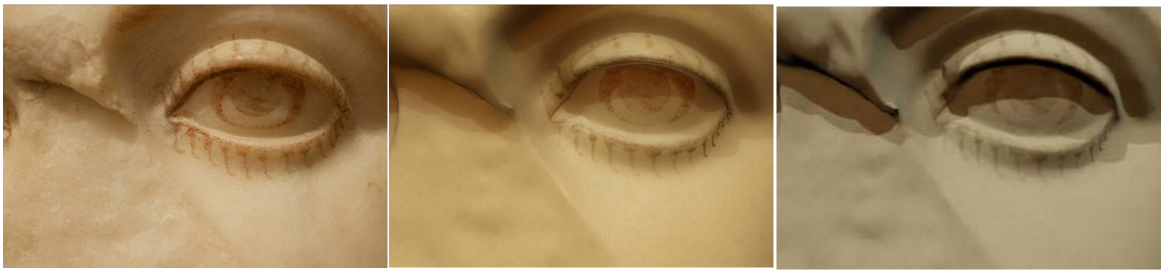

Figure 6: *Left, a photograph of the sample area. Centre a render produced using the pipeline described here. Right, a render made without subsurface scattering and based upon uncalibrated colour data.*

6. Conclusions and Future Work

The simulations and imagery produced using this methodology were sufficiently accurate to be used as interpretive tools and (with the possible exception of the laser scanner) made use of tools widely available to archaeological researchers outside of computer graphics research. The potential utility of the visualisations was greatly increased by the verification process which allowed archaeologists and art historians to gauge the level of accuracy at which the simulations were working and to respond accordingly to these images. The use of verification in this way allowed specialist researchers from outside of computer graphics to engage with these simulations in a decisive and nuanced way and greatly increased the use of the images as interpretive and heuristic tools.

This represented a meaningful step towards the integration of the archaeological visualisation into archaeological practice. An extension of this research would detail this process of integration in more detail and propose methods by which digital visualisations might be even more fully integrated in future.

Further work will also incorporate the application of this methodology to other examples of painted statuary. The methodology was designed to be as general as possible and can be straightforwardly applied elsewhere.

Suitable data have been collected from other examples of polychrome statuary and work, including a comparative analysis of the success of the pipeline, will soon be undertaken and published on these examples.

Figure 7: *A rendered view of the statue with simulated paint.*

The methodology presented here is designed to enable the production of images which are sufficiently accurate that they can function as meaningful interpretive tools. Consequently the pipeline does not include all elements which would be necessary as part of a truly *predictive rendering* approach [WWM*09]. However, subsequent phases of the project will focus upon the contextual analysis of the statues and the dissemination of interpretations. Both of these processes require an approach which places more emphasis on accuracy at the cost of fast production times and flexibility.

Consequently the next stage in the development of this methodology will be to implement a more complete *predictive rendering* pipeline. Spectral rendering will be used in conjunction with appropriate physical scattering and reflectance models and experimentally derived data. Study visits are planned during which data will be collected from the statue using a gonioreflectometer. This stage of the project will also incorporate higher resolution geometric data in order to ensure a greater degree of accuracy.

7. Acknowledgements

The *Soprintendenza Speciale per i Beni Archeologici di Napoli e Pompei* generously provided access to all material and its staff were of very great assistance throughout the complex recording process. The work would have been impossible without the support and knowledge of members of the Herculaneum Conservation Project (a Packard Humanities Institute initiative in partnership with the Soprintendenza and the British School at Rome) and in particular the Director, Prof. Andrew Wallace-Hadrill, its research coordinator Dr Sarah Court and the Director of the British School at Rome Prof. Christopher Smith.

Thanks to Dr Beth Harland at the Winchester School of Art for her assistance in the reconstruction and application of historical pigments. Data capture and advice was undertaken with support from colleagues at the Warwick Digital Lab. Ongoing research has been made possible through the awarding by the Arts and Humanities Research Council of a collaborative doctoral award. This is a formal collaboration between the Herculaneum Conservation Project and the Archaeological Computing Research Group, University of Southampton.

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