BIO-INSPIRED DESIGN FOR ADDITIVE MANUFACTURING - CASE STUDY: MICROTITER PLATE

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ABSTRACT

Bio-inspired design is an innovative methodology for transferring biological solutions into technical solutions, for example for the design of weight- and load-optimized components. Bio-inspired design therefore offers great potential for meeting the challenges of designing additively manufactured components, such as avoiding warpage, supporting structures and material minimisation. Nevertheless, apart from bio-inspired topology optimization tools, bio-inspired design is rarely used in industrial practice because for many companies the practical applicability up to the prototype is not obvious. The aim of this work is therefore a practical approach to the search for biological systems, analysis, abstraction and transfer of analogies. We apply bio-inspired design on the design of a microtiter plate manufactured by stereolithography, whose dimensional accuracy is impaired by warpage. Here, the venus' flower basket, a deep-sea sponge, can serve as a model. It has a hierarchical structure of silicate needles whose elements are abstracted for bio-inspired transfer. We show and evaluate the transfer of different analogies using a prototype.

Keywords: Bio-inspired design / biomimetics, Design for Additive Manufacturing (DfAM), Design-by-analogy, 3D printing, Warpage

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1 INTRODUCTION: CHALLENGES OF ADDITIVE MANUFACTURING

Bio-inspired Design - the search for and transfer of biological solutions into technology - offers a high potential for innovative solutions. "Biological systems are optimized by evolution" (Nachtigall, 2002, pp. 357–388; Fish and Beneski, 2014). In order to survive using as few resources as possible, biological systems are optimized with a focus on energy- and material-efficiency. Therefore, they can serve as a model for the lightweight, load-optimized design for additive manufacturing.
An indication of optimization is the independent development of similar solutions for different unrelated biological systems (Vogel and Ferrari, 2013, pp. 525–527). There are numerous examples of this so-called "convergence" of biological systems of different ancestry. For example, American cactuses and African succulents have similar properties: they have a water-storing corpus and leaves with a small surface to survive in hot, dry climates with little liquid.
Nevertheless, bio-inspired design is rarely used for designing components for additive manufacturing, as it appears to be a very time-consuming method and engineers lack biological knowledge. An exception is the use of bio-inspired topology optimization tools. This paper shows an example of applying bio-inspired design systematically with relatively little effort and biological expertise. The systematic approach implies the use of specific methods for the search for biological models, the analysis and comparison with the technical task, the abstraction of a biological system and the transfer of analogies (Hashemi Farzaneh and Lindemann, 2018).
The procedure for the application of bio-inspired design is shown on the basis of the case study microtiter plate, whose additive manufactured prototypes (stereolithography) do not possess the necessary dimensional accuracy: The dimensional accuracy of components is one of the challenges of additive manufacturing. It can be affected by warpage in thermal processes such as stereolithography (Schmutzler *et al.*, 2016; Klahn *et al.*, 2018, pp. 132–135).
In the following we summarize the occurrence of warpage and the recommended measures against warpage (Chapter 2). We then explain the microtiter plate case study (Chapter 3) and the procedure for new design using bio-inspired design (Chapter 4). The results are finally summarised (Chapter 5).

2 STATE OF THE ART AND RESEARCH

In the following, warpage in laser-based additive manufacturing processes (2.1) and existing solutions to avoid warpage (2.2) are explained.

2.1 Warpage

In laser-based additive manufacturing processes, a laser moves layer by layer through the desired component geometry and injects energy into the component layers. In stereolithography, the ultraviolet light of the laser triggers an exothermic photoreaction: Radicals are formed in the reaction resin. They trigger polymerisation and thus the curing of the resin. Both polymerisation and cooling cause shrinkage. Each layer is connected to underlying, already firmer layers. The shrinkage is hindered by the connection with already cured material. This results in residual stresses which can lead to warpage. The warpage depends on the temperature difference between the component layers, the material and the geometry. Flat components in particular are affected by warpage. The components can distort to such an extent that a collision between the tool and the component can occur during the application/melting of further component layers (Klahn *et al.*, 2018, pp. 113–114; Wiedemann, 1997, pp. 20–28; Gebhardt and Hötter, 2016, pp. 45–56).

2.2 Current solutions to avoid warpage

To avoid warpage, process parameters can be modified, and adjustments can be made during the design of the component.
The modification of process parameters includes the preheating of individual powder layers (e.g. laser sintering), the resin bath (e.g. stereolithography) or the heating of the installation space (e.g. fused deposition modelling). This reduces the temperature difference between the molten component layer and the already cured component layer and results in lower residual stresses. A further process modification is the optimization of the exposure path of the laser so that the energy input is as uniform

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as possible. However, this is only possible if there is access to the control of the laser (Schmutzler *et al.*, 2016; Klahn *et al.*, 2018, 113–115, 132–135; Formlabs, 2018).
In addition, the arrangement of the component in the building space can be modified, i.e. flat elements of the component should be aligned perpendicular to the design plane. If there are several flat elements aligned in different directions, this is impossible. In addition, the vertical arrangement of flat elements can result in more support structures for other elements. Support structures can also be attached directly to flat elements. This measure should achieve a more uniform cooling and fix the flat elements threatened by warpage. However, support structures have to be removed in a time-consuming manner.
For designing flat components, another recommendation is the use of ribbed reinforcing structures. Their function corresponds in principle to that of supporting structures (more uniform cooling, fixation). However, it is often not possible to attach ribs to functional surfaces in particular (Klahn *et al.*, 2018, pp. 132–135).
In summary, there are suggestions for process modification to avoid warpage. However, these cannot be implemented in all cases. Few general design recommendations are made in the technical literature. Consequently, there is a great potential for innovative designs, which we will address through the use of bio-inspired design.

3 CASE STUDY: MICROTITER PLATE

A microtiter plate serves as a case study for a warpage-affected design. Microtiter plates are used for the examination and cultivation of microbiological samples. The plates have a number of cavities. In each of the cavities, a single sample is placed. The plates are closed by a lid with which each sample can be fixed (American National Standards Institute/ SLAS Microplate Standards Advisory Committee, ANSI-SLAS 2004-2012)
In a research project, an initial prototype for the microtiter plate shown in Figure 1 and the matching lid were designed for additive manufacturing using stereolithography (SLA printer) (see Gerber *et al.*, 2019 for details). The prototype has tubular recesses for the sample holder and the lid has matching cylinders that hold the samples in place.

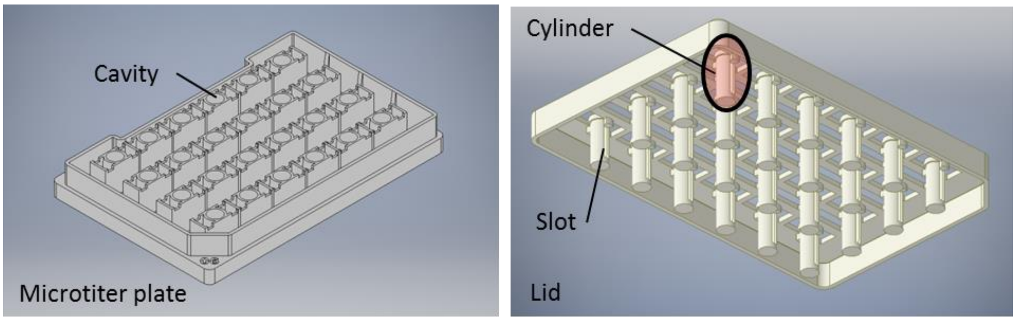

Figure 1: Microtiter plate (left) and lid (right) - conventional design (initial prototype)

The cylinders have a slot and are hollow. The slot is used to check the samples: If the cylinders do not rest on the specimens due to any faults, such as an uneven surface, liquid enters through the gap and the specimen is detected as faulty (Gerber *et al.*, 2019).
Approximately ten prototypes of the microtiter plate and the lid shown in Figure 1 were manufactured using a SLA formlabs printer (stereolithography). In several cases, the cylinders of the cover do not fit into the recesses of the microtiter plate. Conducting initial measurements with a calliper, we observed that the cylinders were slightly deformed along the middle axis and the slots were slightly bulbous at the middle. The inaccuracies therefore occur in-between the layers during the stereolithographic curing process. From this observation, we assumed that warpage is a plausible cause for the inaccuracies.
For this work, we analysed this assumption further: two sections of the microtiter plate's lid were manufactured. In order to analyse the effect of warpage on the single cylinders, these were measured with gauges, i.e. sleeves with bores of several diameters in steps of 0.1 mm. Using sleeves allowed us to determine one value that summarizes several inaccuracies of the diameters relative to the middle axis of the cylinders, e.g. varying diameters or slate axes. The resulting distribution of cylinder inaccuracies is depicted in Figure 4.
Using bio-inspired design methods, a new concept is developed that replaces the simple cylinder shape in the lid with a less "warpable" and more "robust" design.

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4 PROCEDURE FOR NEW DESIGN USING BIO-INSPIRED DESIGN

The application of bio-inspired design comprises a number of activities for which different methods can be used. On the one hand, the development approach plays a role: A fundamental distinction is made between the so-called *biology push* and the *technology pull* approach. If we adopt the biology-push approach, development is based on the identification of a biological "solution" for which a technical application is sought. The case study presented here, on the other hand, follows the technology pull approach: there is a technical problem for which a biological model is sought (Association of German Engineers, 2012; Hashemi Farzaneh and Lindemann, 2018).

The "scenario" of biological development also plays a role: Bio-inspired design can be used, for example, in creativity workshops as well as in long-term research projects in which engineers and biologists collaborate and conduct research together. In our case study, we are dealing with the application of biological knowledge, i.e. no biological research is carried out (Hashemi Farzaneh and Lindemann, 2018).

The targeted application of bio-inspired design includes the following activities and methods:

- The search for biological systems (4.1)
- The analysis and comparison of biological and technical systems (4.2)
- The abstraction of a biological system (4.3) and
- The transfer of analogies from biology to technology (4.4)

These activities are explained on the basis of the new design of the microtiter plate.

4.1 Search

Two basic strategies can be distinguished in the search for biological systems:

The first strategy, the intuitive or creative search, uses personal knowledge as a resource. This approach can be particularly successful if experts from biology and technology collaborate in interdisciplinary teams. It can be supported by creativity methods such as *Method 6-3-5* (Lindemann, 2009, p. 278; Feldhusen *et al.*, 2013, p. 357) or *Synectics* (Gordon, 1961)

The second strategy, on the other hand, relies on documented information. It is possible to search for biological information (e.g. in biology books and publications from biological research) or for information that has been prepared for bio-inspired design. This approach requires less biological expertise and search time.

In this work, therefore, we focus our search on documented information prepared for bio-inspired design and use the database *asknature.org*. Catalogues for bio-inspired design (Hill, 1997; Gramann, 2004; Löffler, 2009) and databases (asknature.org) can be used for this purpose. For the search in catalogues and databases, a search query must be formulated using functional terms. Table 1 shows our search terms.

Table 1: Search terms and results (based on Hashemi Farzaneh et al., 2018)

Search terms			**Search result**
Verb	**Noun**	**Property**	**(asknature.org)**
Prevent	Warpage		Plant cells[1]
Prevent	Distortion		No suitable result*
Prevent	Misshaping		Same result as for "prevent warpage".
Resist	(Shear) force		bug[2]
Resist	Temperature		No suitable result*
Increase	Moment of resistance		No suitable result*
Dissipate	Hot	Uniform	Desert snail[34]
Associated function asknature.org:			
Manage	Tension		Venus' flower basket[5], plant leaf[6]

*Non-fitting results contain several parts/liquids/elastic components

[1] https://asknature.org/strategy/walls-prevent-collapse-under-tension/#.W2dM3MJCSpo
[2] https://asknature.org/strategy/insect-elytra-resist-shear-and-cracking/#.W2dR5cJCSpo
[3] https://asknature.org/strategy/shape-shades-and-enhances-heat-radiation/#.W2dTycJCSpo
[4] https://asknature.org/strategy/shell-protects-from-heat/#.W2dVFMJCSpo
[5] https://asknature.org/strategy/silica-skeleton-is-tough-and-stable/#.W2dOrsJCSpo
[6] https://asknature.org/strategy/leaves-resist-gravitational-loading/#.W2dRLsJCSpo

Here, functions are formulated using a verb and a noun. The technical problem is abstracted either to the occurring forces by residual stresses (prevent warpage/distortion/misshaping; resist force, increase moment of resistance) or with respect to the occurring heat (dissipate heat). In addition, Helms (2016) recommends using search terms for properties and environment (*BIOscrabble* method). Therefore, the functional term *dissipate heat* is supplemented to the property *evenly distribute heat* (*dissipate heat AND uniform*). The database asknature.org is based on its own functional classification. Based on this functional classification, several search results were assigned to the function *manage tension*. This function was then also used as a search term.
Table 1 shows six matching search results. All search results that consist of several components, contain liquids as part of the solution or contain elastic components were sorted out as unsuitable. The six remaining results are analysed below and compared with the technical task of redesigning the microtiter plate.

4.2 Analysis/comparison

The structure of biological and technical systems differs greatly. Biological systems are always multifunctional, i.e. they fulfil a multitude of functions, the majority of which are irrelevant for a single bio-inspired design. In addition, biological systems are hierarchically structured, i.e. each "size level" of the biological system, from the molecular level to the integral level, contributes to the fulfilment of the functions. Often a biological solution can be scaled, but the influence of heat transfer, fluid flows and forces on the different size levels must be considered (Hashemi Farzaneh and Lindemann, 2018, p. 203).
When considering the six biological systems that were identified in the search (4.1), two aspects stand out in which the biological systems differ from each other and from the technical task. Table 2 shows a summary.

Table 2: Comparison of biological systems (based on Hashemi Farzaneh et al., 2018)

Biological system	**Description**	**Comparison to design of cylinders in the lid of the microtiter plate**	
		shape	**load**
Plant cells	Spiral-shaped thickenings support the cell walls of elongated cells that serve to transport water.	Similar	Internal pressure (water)
Bug	Cover wings (elytra) consist of several elastically connected layers	Different (flat wings)	Forces through flapping wings
Cactus	Ribbed structure of the body provides cooling, shade and reduces the area that is shone vertically by the sun	Similar	Sun/Heat
Desert snail	The snail's shell reflects the main part of the solar radiation, in heat the snail pulls its body far up into the snail shell and avoids contact with the hot desert ground.	Different (snail shell)	Sun/Heat
Venus' flower basket (deep sea sponge)	Almost cylindrical venus' flower baskets consist of silicon fibres, which are structured from the nano- to the macro- level in such a way that the overall structure is stable, yet flexible.	Similar	Forces due to water flow and pressure in the deep sea
Plant leaf	Central veins support flat plant leaves. They have round cells filled with liquid on the underside (absorbing compressive forces) and elongated cells on the top (absorbing tensile forces).	Different (flat leaf)	Gravity

The first aspect is the shape of the biological system to be supported: only three of the biological systems have a shape comparable to the cylinders (plant cells, cactus, venus' flower basket), while the biological systems *beetle* and *plant leaf* have flat structures. The desert snail has an approximately

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pyramidal shape. The shape is not an exclusion criterion, but the biological systems with a similar shape to the technical task are considered first.
The second aspect is the type of exposure: the cactus protects itself from solar radiation through its shape. This is comparable to the heat introduced by the laser in the stereolithography process. However, an initial prototype of a cactus shape showed no improvement in dimensional accuracy compared to a simple cylindrical shape.
The plant cells are strengthened by the spiral-shaped reinforcement against the internal pressure by water. The venus' flower basket also has a spiral structure for reinforcement against external forces. Its elements on the upper hierarchical levels are shown in Figure 2. Its skeletal walls are reinforced by spiral combs. The network of silicate needles forming the skeletal walls consists of a cross-shaped lattice of silicate needles. In addition to horizontally and vertically arranged silicate needles, there are diagonally arranged silicate needles. The silicate needles themselves have different shapes. They consist of a composite material with cement and needle layers containing organic and inorganic components (Weaver *et al.*, 2007).
Section 4.3 abstracts the structures of the venus' flower basket, since its hierarchical structure offers different possibilities for the transfer of analogies. This includes the consideration of the spiral structure, which also occurs in the plant cells.

Hierarchical level	elements
entire skeleton	cylinder shape
skeletal walls	anchorage in the ground, cap, spiral comb, slightly conical shape
Network of silicate needle bundles	cross-shaped grid of silicate needles, additionally diagonal silicate needle bundles
silicate needles	anchoring needles, different silicate needle shapes (2-,4-,6-beam), non-planar cross-shaped silicate needles
composite material	Cement layer, needle layer
Organic and inorganic components	Nanoparticles of silicate, organic interlayer, axial protein fibers

Figure 2: Venus' flower basket[7] (left) and hierarchical levels (right) (according to Weaver et al., 2007, Hashemi Farzaneh et al., 2018)

4.3 Abstraction

Biological systems can only rarely be applied directly in the technical domain. This is usually only possible at the molecular level, since the complexity of biological systems increases at different size levels due to their hierarchical structure (Sartori *et al.*, 2010). The elements relevant to the bio-inspired design task must therefore be identified and abstracted for transfer into the technical domain.
Figure 2 shows the elements of the venus' flower basket on different hierarchical levels. For the new design of the cylinders of the microtiter plate the material cannot be changed, therefore we limit ourselves to the higher hierarchy levels:

- Total skeleton: hollow cylinder shape
- Skeletal walls: The anchoring in the ground and the cap of the glass needle sponge are not relevant for the microtiter plate. The skeletal walls are reinforced by a spiral (similar to the spiral reinforcement of the plant cells).
- network of silicate needle bundles: cross-shaped grid of horizontal and vertical silicate needle bundles, additional diagonal silicate needle bundles

[7]Foto: Euplectella aspergillum at 2572 meters water depth. California, Davidson Seamount, by NOAA/Monterey Bay Aquarium Research Institute, http://www.photolib.noaa.gov/htmls/expl0900.htm

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4.4 Transfer

Bio-inspired design does not mean copying a biological system by technical means, but it implies the transfer of a suitable analogy. The abstraction of the structure of the venus' flower basket (Figure 3) shows a starting point for the transfer of analogies to the new design of the microtiter plate. Biological analogies are characterized in particular by their degree of abstraction. It is useful to formulate analogies with varying degrees of abstraction and to check their applicability. For the new design of the microtiter plate, the elements of the different hierarchy levels abstracted in section 4.3 are considered:

- The **hollow cylindrical shape** (level: total skeleton) corresponds to the existing design of the cylinders of the lid of the microtiter plate.
- The **spiral-shaped reinforcement** (level: skeletal walls) seems particularly interesting for a transfer, since it also occurs in plant cells. This convergence is an indication of a particularly successful biological solution (see Vogel and Ferrari, 2013, pp. 525–527).
- The **lattice structure** (level: network of silicate needle bundles) reinforces the cylindrical shape and supports it against vertical and horizontal forces. However, the in the grid is arranged in the cylinder envelope plane instead of the horizontal plane: the grid thus forms the cylinder envelope with rings and vertical elements.
- The **diagonal reinforcement** (level: network of silicate needle bundles) additionally strengthen the lattice structure. For the microtiter plate, this element seems less useful than the spiral reinforcement and the lattice structure.

For a first prototype, the hollow cylindrical shape, the spiral reinforcement and the lattice structure are used. If this prototype does not meet the requirements, in a next step, for example, only the spiral structure can be used (more flexible design), or additional diagonal reinforcements (more stable design). The prototype is shown in Figure 3.

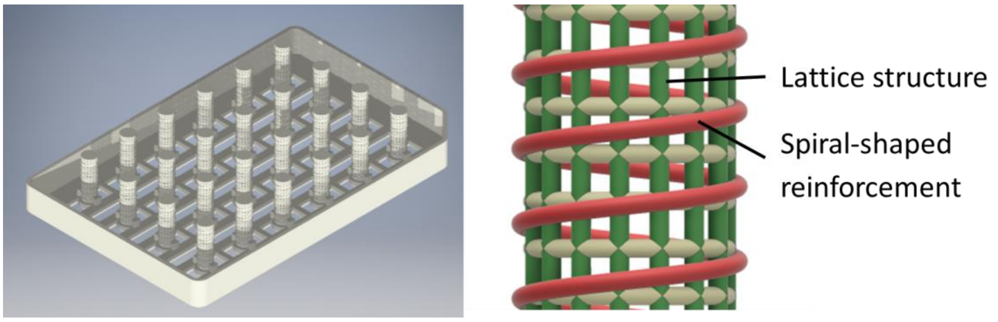

Figure 3: Prototype bio-inspired design of the lid of the microtiter plate and schematic structure of a cylinder (right) (based on Hashemi Farzaneh et al., 2018)

The cylinders in the lid of the microtiter plate were replaced by the bio-inspired design. Its schematic structure consists of the lattice structure in the unwound cylinder envelope plane (vertical supports, rings) and a spiral-shaped reinforcement. The cylinders are provided with a round functional surface that fixes the samples on the microtiter plate.

5 RESULTS AND CONCLUSION

Two prototypes of the new bio-inspired design of the lid of the microtiter plate are manufactured analogous to the conventional design shown in Figure 1. As for the conventional prototypes, two sections of the bio-inspired lid are made with a formlabs 3D printer (stereolithography). Figure 4 shows the distribution of the diameter measurement with a gauge.

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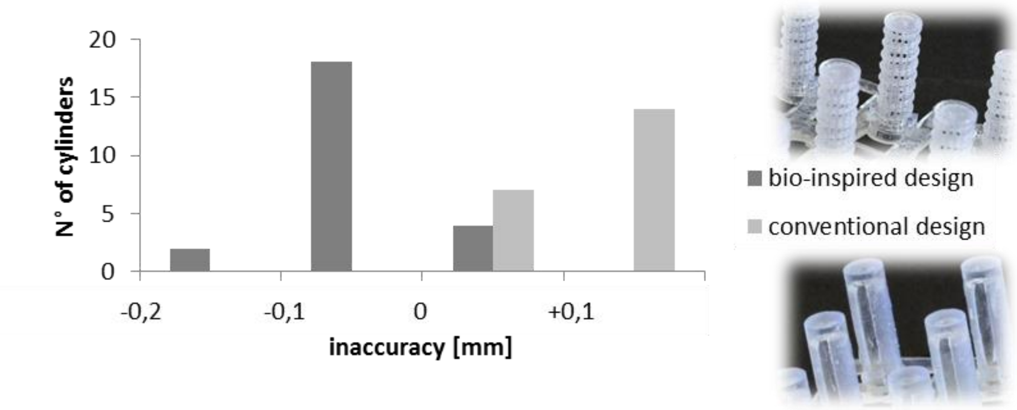

Figure 4: Conventional and bio-inspired prototypes - Distribution of the inaccuracy [mm] of the cylinder diameters measured with gauges

The majority of the bio-inspired cylinders have an inaccuracy between 0 and -0,1mm, whereas the majority of the conventionally designed cylinders have an overall inaccuracy >0,1mm. Using the Mann-Whitney-U test (non-parametric statistic test, also called Wilcoxon rank sum test), it is confirmed with a significance level of α=0.1% (two-sided test) that the bio-inspired prototypes of the cylinders are more accurate than the conventional prototypes (Mann-Whitney statistics: bio-inspired design U'=21, conventional design U''=483, critical value U*=103 for number of samples n=20, m=24, values from Milton (1964)). In contrast to the conventional prototype, the cylinders of the measured bio-inspired prototype therefore fit into the microtiter plate shown in Figure 1. There is no "jamming" of the lid and base plate, as is the case with the tested conventional prototype.

The result shows that the bio-inspired design of the cylinder elements is more robust against warpage. Regarding the measured prototypes, the bio-inspired cylinder elements are more dimensionally accurate than the conventionally designed cylinders. In addition, the warpage of the flat cover structure seems to have less influence on the functionality of the cylinders. This is attributed in particular to the flexibility of the bio-inspired design.

In summary, this work shows how the potential of bio-inspired design can be used for the design of additively manufactured components: Methodical searches, for example in databases such as *asknature.org*, can identify a large number of biological systems. These must then be analysed and compared with the technical task at hand. The elements of one or more biological systems must be abstracted before analogies are transferred to develop a technical solution.

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