FROM PHYSICALLY KNITTED MODELS TO CALIBRATED DIGITAL SIMULATIONS: A WORKFLOW BASED ON THE BEHAVIOR AND GEOMETRY OF THE KNITTED TENSIONED STRUCTURES

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The author of this paper proposes a workflow that is developed based on the behavior and geometrical characteristics of knitted textiles. The overall goal is to enhance the implementation of knitted tensioned structures for architects and architecture students to use this material during the design process. The workflow includes eight main steps that are not necessarily in sequence: 1) Rough illustration of the overall form, 2) Developing knitting diagram for the desired shape, 3) Knitting physical models, 4) Physical form finding, 5) Digital simulation, 6) 3D scanning, 7) Overlapping form found and 3D scanned meshes, and 8) Calibrating digital model. The output of this process would be a tuned digital mesh that could be used as an input for further structural analysis, such as external wind/snow loads.

Additionally, the author highlights the different architectural form development strategies using knitted textiles. The emphasis is on understanding knitted textiles characteristics through making and elaborating the methods to input material behavior and geometry into digital simulations. The digital model is then calibrated using optimization methods to approximate its physical counterpart. Knitted textiles are new architectural materials that offer potential such as flexibility and seamless 3D knitting. Such characteristics allow for the development of more complex shapes, however, making predicting the behavior and shape of these materials more challenging. In general, there is a spectrum of possibilities to develop an architectural form using knitted textiles. At one extreme, one can knit a planar shape using stretchy yarns or knit patterns. At the other end, a final shape can be knitted to the exact desired form with non-stretchy yarns and patterns. Nevertheless, there are some other possibilities in between. A form can be knitted in a rough, simplified, and semi-3D shape, and then by implementing external forces, the final shape will emerge. Form development with simplified knitted shapes is the focus of this research. The author will explore the methods to correlate physical modeling with digital simulations of tensioned knitted textile structures by making samples and digitally simulating the models.

Keywords: Knitted textile, form finding, prediction, initial shape, form development, calibration, 3D scanning.

INTRODUCTION

Although dominant material in textile design/industry, knitted textiles are new materials in architecture. Flexibility, multi-directionality, and interconnected structure of the knits are essential properties of knitted textiles, allowing these materials to be considered for developing more complex architectural shapes. However, successful implementation of knits in architecture requires a deep understanding of their structures for making architectural forms.

Form development using knitted textiles requires consideration of three embedded scales in the structure of knitted fabrics, including micro-, meso-, and macroscale (Oghazian and Vazquez 2021). Microscale is the scale of one stitch, or one loop made by moving continuous yarn through previously made stitches. The adjacency of multiple stitches will create a piece of textile that adds structure to the fabric and it is called mesoscale in this research. The overall form of the models made of aggregated parts of mesoscale materials or using a seamless knitting technique is called macroscale.

Developing the overall form for the desired shape is challenging because there is no unique method for generating the form. Taking advantage of the characteristics of the knitted textiles, one can knit a form in a spectrum of possibilities, and based on the method chosen, different knitting diagrams will be generated, and therefore, knitting machines with specific capabilities are required. Implementing knitted textiles in textile design reveals different form-fitting strategies based on the body dimensions and curvatures such as studies by Kaspar (2019) and Yang (2010). Similarly, in this research, I elaborate on the various form development approaches to fit architectural forms and shapes.

1. FORM DEVELOPMENT WITH KNITTED TEXTILES

Knitted textiles are used broadly as materials for developing 3D shapes in textile design. In the last two decades, these materials have started to be used in architecture due to many potentials of knits and advancements in CNC knitting (Ahlquist 2015; Sabin 2013; Thomsen, et al. 2016). This section highlights different approaches to developing forms within these research areas.

Developing knitted tensioned forms with knitted textiles depends on the initial shape knitted, level of the elasticity of the textile and forces applied. The first two elements are also dependent on the yarn type, knitting patterns, and the tension applied to the yarn during the knitting process. Based on the many implementations of knitted materials in literature, the author argues that the shape and the behavior of 3D knitted structures for developing tensioned structures can fall in a spectrum of full force/no form to full form/no force, as illustrated in Figure 1.

This means that textiles can be knitted in a planar shape made of either stretchy materials or knit patterns that add to the elasticity of the textiles (Figure 1_Left). These knitted materials must be under full external force to get the final shape. The methods used by Baranovskaya, et al. (2016), McKnelly (2015), Ahlquist (2015) belong to this category. On the other extreme, textiles are knitted in a desired 3D shape without needing an external force or minimum force to obtain the final form (Figure1- Right). Methods developed by Liu, et al. (2020), Popescu, et al. (2018) are representative of this category. In this approach, the yarns used for making the models should have the least elasticity, and the patterns should add no stretchability to the knitted textile. Generating diagrams is more complicated in this method, and there are some limitations to developing the mesh configurations depending the typology of the overall form and possibility of the knitting the whole structure seamlessly (Liu, Li, and Yuan 2020). The third approach is to knit semi-3D shapes in a rough initial shape with a simple mesh configuration. The models between the two extremes need a proportional force/form to obtain the desired

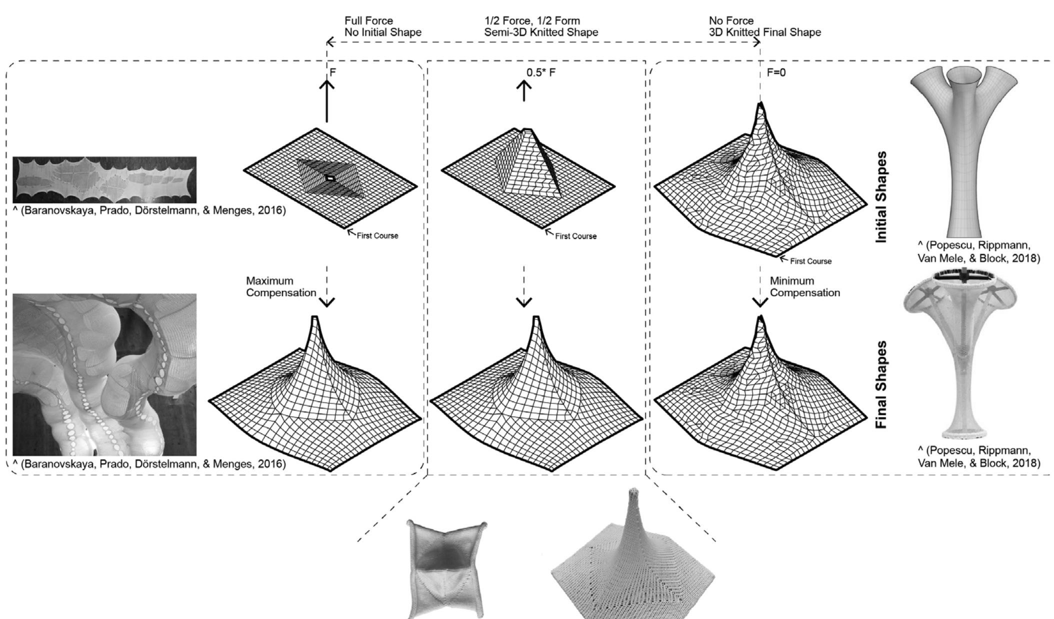

Figure 1: Spectrum of approaches in architectural knitted tension structures using knitted textiles. Source: Revised based on Oghazian, et al. 2021. Additional images from Baranovskaya, et al. (2016) and Popescu, et al. (2018).

shape. The third approach is the focus of this research, where we will get a relaxed shape out of a rough and simplified knitted textile. The most advantage of this approach is that the digital simulation is much simpler and compared to the two ends of the spectrum, it is possible to knit the forms with simple tools such as pegboards, looms and hand-held knitting machines as well.

There are differences regarding the knitting diagrams, knitting processes, and the knitting machine potentials required for knitting the models associated with each of the aforementioned methods. For example, the left category of Figure 1 requires a change in the knit structure for one course and within different courses. Although the shape is planar, for obtaining the desired shape under external force, the textile should have a gradient effect, such as varied looseness in different sections of the fabric. The right category of the spectrum in Figure 1 also requires manipulation in the knitting of different parts of the model by putting stitches on hold and transferring the stitches between two beds of the knitting machine. Therefore, two ends of this spectrum will benefit a lot from CNC knitting machines and their capabilities for automatic knitting. However, other approaches in-between require adding some level of 3D dimensionality to the textile of the consistent knit structure which makes them easier to knit and are knittable with more simple knitting machines, pegboards, and looms.

The overall tensioned form is dependent on the initial shape knitted and the force applied. If we could formalize the correlation between the initial shape, final shape, and the force required to obtain such shapes, then it would be easier to develop complex architectural tensioned forms considering architectural and structural requirements. In the following of this section, the author elaborates more on the differences between these three form development strategies. Finally, a workflow is proposed to enhance the study of knitted textile structures for developing architectural forms.

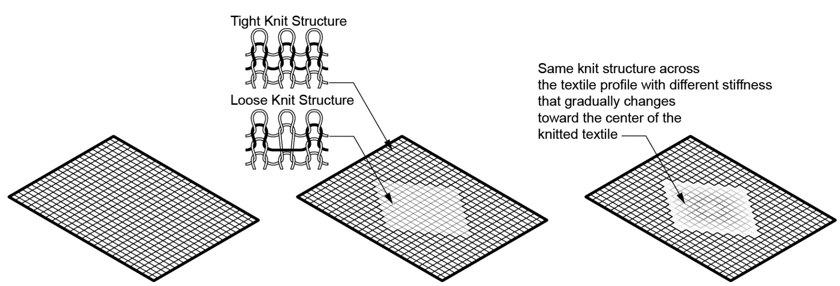

Figure 2: Variations in structure of knitted textiles to change its behavior. Left: Simple knit structure across the model; Middle: Change of pattern in the middle of the textile; Right: Change of tension settings in the middle of the textile. Source: Author 2021.

1.1. PLANAR INITIAL SHAPE

Yarn type, knit structure (patterns made of a sequence of different stitch structures), and tension applied on the yarn during the knitting process by yarn holder and carriage are some of the main elements that affect the looseness and initial quality of the overall knitted textile. Such qualities also affect the shape and curvature of the models that emerge after applying external forces. In this approach, the initial shape is a planar surface knitted flat. A basic model in this category is a planar shape with a consistent pattern across the knitted textile structure. Using a monotonous pattern, it would be hard to manipulate the behavior of the textile for a particular overall shape. Therefore, the textile could be graded by differentiating the looseness in different sections of the textile, either by changing the tension settings, stitch structure or yarn thickness. Figure 2 shows some of these different strategies.

1.2. SEMI-3D AND ROUGH INITIAL SHAPE

The second approach is to knit a semi-3D and rough shape and then apply external forces to obtain the desired shape. In this approach, the final shape is dependent on both the initial shape knitted and the external force. However, the dependency of the final form on each of these elements is different based on the closeness of the strategy to either ends of the spectrum. Figure 1- middle shows one case study of a rough 3D knitted cone that is seamlessly attached to a planar rectangular fabric. The more detailed process of physical form-finding, digital simulation, and calibrating a digital model for a tensioned knitted textile model that belongs to this category of form development strategies will be presented in section 2.

1.3. FULLY 3D INITIAL SHAPE

The third approach is knitting the full 3D shape exactly as desired. This approach will minimize the compensation and external forces required to fixate the final form. However, the elasticity of the knitted textile should be decreased. Research in textile design shows the possibility of generating adequate diagrams for making complex shapes considering the potential of knitting machines such as Shima Seiki, as proposed in a study by Narayanan, et al. (2018) and McCann, et al. (2016). However, there are limited platforms for architects to design and generate such diagrams. Popescu, et al. (2018) has developed an algorithm that creates a distribution of stitches for patches of complex forms. Cockatoo, a plugin for Grasshopper, recently offered by Max Eschenbach, is an open-source software toolkit for generating 3d knitting patterns from NURBS surface and mesh geometry (Eschenbach 2021). Figure 3 illustrates different stitch distributions generated using this tool. However, not all the configurations are suitable for knitting. Knittability of the models using the diagrams generated by this plugin is the subject of another ongoing research. It should be also mentioned that it is difficult and in some stitch configurations it is even impossible to knit the model using simple and manual knitting machines because it requires to keep track of the stitches that should be stayed on hold or transferred between the beds within each course and between the beds.

In summation, regardless of the approaches mentioned above, the model's overall size will be affected by the type of the yarn, knit structure, and tension applied to the yarn during the knitting process. By changing the method of developing the initial shape, the level at which each element affects the behavior of the tensioned knitted textiles might differ. Additionally, based on the control users seek to have on the overall form, either of these approaches might be implemented during the design process. In this research, we are looking at enhancing the use of knitted textiles for architects and architecture students

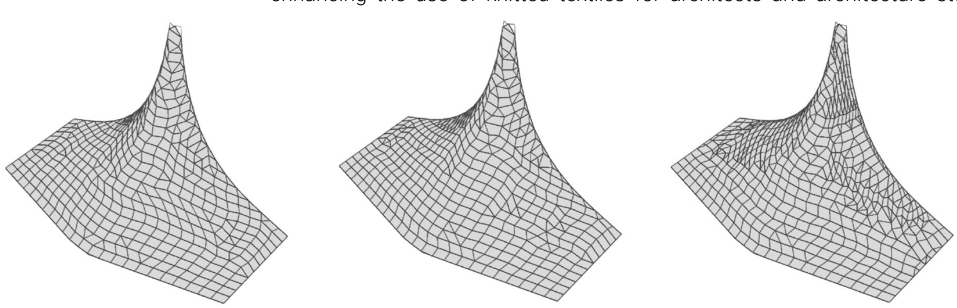

Figure 3: Stitch distribution over the half of desired 3D form using Cockatoo plugin in Grasshopper developed by Eschenbach (2021). Source: Author 2021.

for form development in the simplest way. The available tools for making the knitted samples significantly affect the approach chosen for developing such forms. Therefore, we emphasize the middle category as one of the methods of generating 3D architectural forms using simple devices. In the next section, a workflow is introduced that highlights consecutive processes from physical to tuned digital models for this kind of tensioned knitted textile structure.

2. A WORKFLOW FOR IMPLEMENTATION OF TENSIONED KNITTED TEXTILES

In this section, a workflow for developing tensioned knitted textiles is introduced. The process is illustrated in Figure 4.

The method includes eight main steps that are not necessarily in sequence. 1) Rough illustration of the overall form 2) Developing knitting diagram for the desired shape, 3) Knitting physical models, 4) Physical form-finding, 5) Digital simulation, 6) 3D scanning, 7) Overlapping form found and 3D scanned meshes, and 8) Calibrating digital model using optimization techniques.

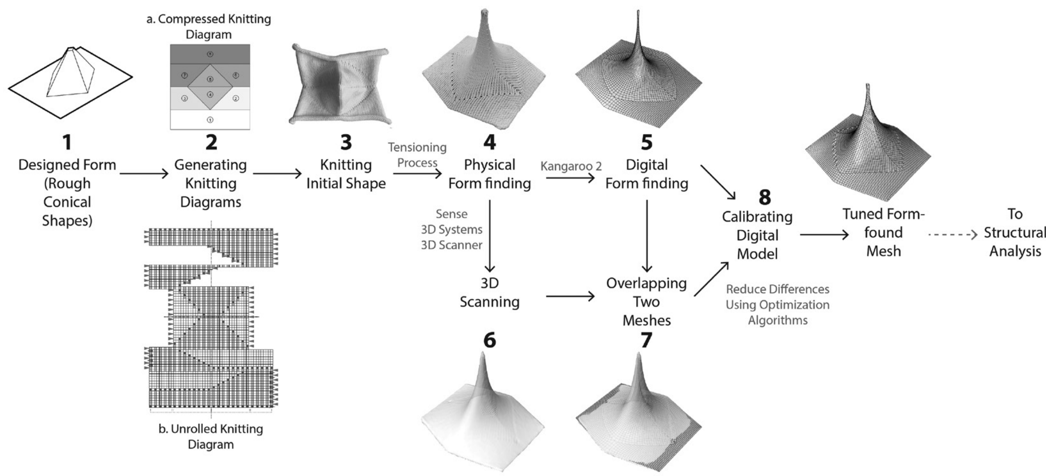

Figure 4: A workflow from physical modeling to the digital simulation of knitted tensioned structures. Source: Author 2021.

2.1. KNITTING PROCESSES AND PHYSICAL FORM-FINDING (STEPS 1,2,3,4)

The physical form-finding of the tensioned knitted textiles comprises the first four steps of the workflow. For a desired conical shape, a rough shape is generated first, and the knitting diagrams are designed. There are two types of graphs for this step: the first is a compressed diagram that helps to understand the sequence of knitting the different parts of the model (Figure 4- step 2, diagram a), and the second diagram is the unrolled diagram that illustrates the process of making every individual stitch (Figure 4- step 2, diagram b). In this study, a simple single-bed Silver Reed knitting machine is used for making the samples. Therefore, it was essential to generate the knitting diagram in a way that is knittable by this machine. After knitting samples, the boundary conditions and the external forces are defined to give the final shape to the flexible knitted piece. This process is called physical form-finding. These four steps are shown in Figure 5 for different double conical shapes knitted with the same machine and the same pattern.

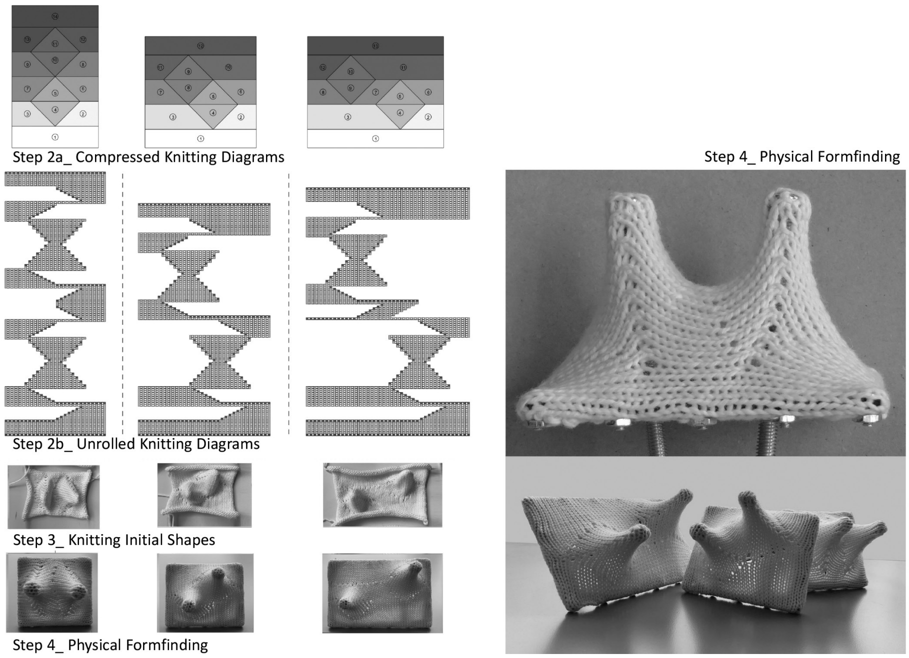

Figure 5: Generating knitting diagrams, knitting, and physical form finding for different double conical shapes. Source: Author 2021.

2.2. DIGITAL SIMULATIONS (STEP 5)

The fifth step of the workflow is digital form-finding. Knitted textiles are flexible materials that possess some level of uncertainty in their behavior because of the characteristics that emerge in the formation process. Therefore, it is challenging to input such properties during the simulation process. Tools such as Kangaroo 1 and 2, which use Dynamic Relaxation and the Projective Constraint method, respectively, are immensely powerful for explorative form-finding of flexible materials. They require the user to specify lengths and stiffnesses or related model properties to get an accurate representation of the tensioned shape. The digital modeling at this step is based on the model developed in our previous research using Kangaroo 2 (Oghazian, et al. 2021). To simplify the simulation process, a quad mesh face is used to represent a stitch. The change of the length and stiffness of these mesh edges are in which the properties of the knitted textiles under the tension are input during the form-finding process.

2.3. CALIBRATION PROCESS (STEPS 6,7,8)

In the digital model developed for simulating the knitted textile models by Oghazian, et al. (2021), the values for the length factor and stiffness are adjusted manually. To automate the process and tune the digital model, a calibration process is developed that requires 3D scanning of the physical models. This 3D mesh and the formfound mesh will then be overlapped. An objective is defined to minimize the distance between the two meshes. For this step, the implementation of different optimization plugins is studied as tools for tuning the digital model. The length factor of the meshes is the variable, and the cumulative distance between the meshes is the objective of the optimization process. A more detailed comparison between the performance of different optimization algorithms for this model can be found in Oghazian, et al. (2022). In the calibrated model presented in Figure 4 at step 8, GN-ORIG-DIRECT-L from Radical/ DSE plugin is used as the best optimization algorithm for this process.

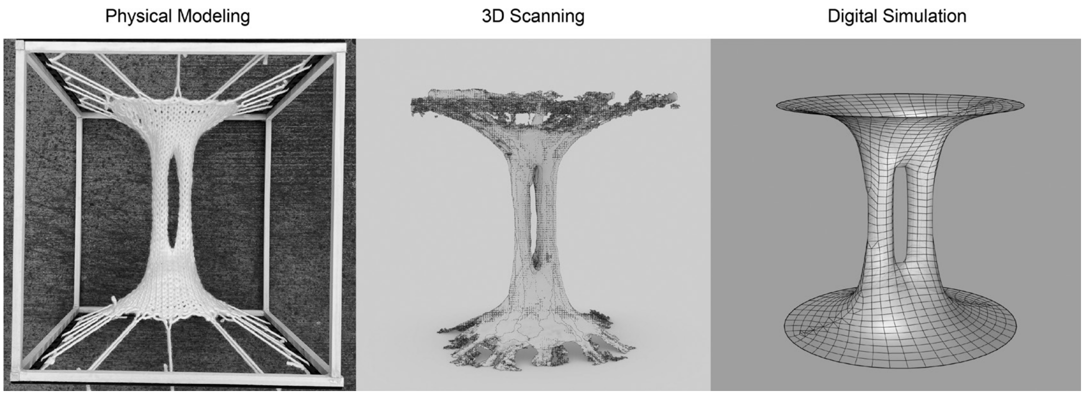

Figure 6: Physical Modeling, 3D scanning, and Digital Simulation. Source: Yu Shi.

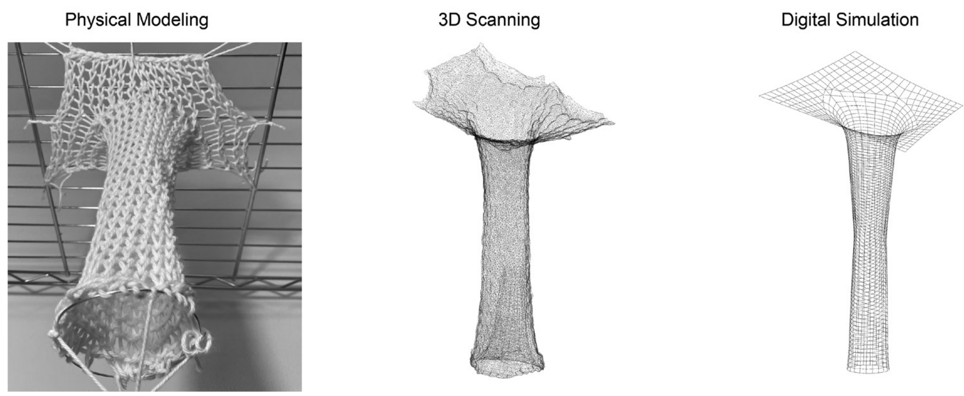

Figure 7: Physical Modeling, 3D scanning, and Digital Simulation. Source: Daniel Robert Pawluczyk.

The output of the process is a tuned mesh that can be used as an input for structural analysis. It is important to have a reliable formfound mesh to do the structural analysis and study the behavior of the material under external loads. The whole process was validated through the development of different knitted tensioned structures within a Design Research Studio (DRS) course for Lightweight Tensioned Structures that was offered by Felecia Davis and the author at Penn State University during Spring 2021 and 2022. Two examples of the initial projects are illustrated in Figures 6 and 7.

3. CONTRIBUTION

In this research, different form development strategies using knitted textiles are introduced. Additionally, a workflow is proposed that includes various processes from physical modeling to tuning digital simulations for developing 3D architectural forms using knitted textiles and knitting techniques. The process is mainly illustrated for the models that have a semi-3D rough knitted initial shape and are dependent on both the initial shape and external loads to obtain the final tensioned shape. However, the whole process is applicable to developing any form of development approach discussed in the paper.

ACKNOWLEDGEMENTS

This research was partly funded by SCDC Student Research Grant and ICDS Seed Grant at Penn State University.

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