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Investigation of Printing Parameters on Dimensional Accuracy of Geometrically Complex Objects in FDM 3D Printing

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ABSTRACT

This study examines the effects of seven key printing parameters—bed temperature, nozzle temperature, nozzle diameter, print speed, infill density, infill angle, and layer height—on the dimensional accuracy of geometrically complex parts, such as screws and nuts, fabricated using Fused Deposition Modeling (FDM). Utilizing an L8 orthogonal array within a design of experiments (DOE) framework, the parameters were analyzed for their influence on both overall and detailed dimensional characteristics across length, width, and height axes. The results reveal that layer height, nozzle diameter, and bed temperature significantly impact dimensional accuracy, with interactions between factors playing a crucial role. The maximum observed variation was 4 % for screw diameters and 7 % for nut diameters. Findings highlight the importance of optimizing parameter interactions to enhance accuracy and the practical utility of Taguchi's methodology in reducing experimental complexity. This research provides valuable insights for improving the precision of 3D-printed components, particularly in applications requiring complex geometries. Prog. Color Colorants Coat. 18 (2025), 493-502© Institute for Color Science and Technology.

1. Introduction

Three-dimensional (3D) printing has emerged as an innovative manufacturing technique, gaining significant interest from scientists, especially in polymer fabrication. This growing attention has spurred the investigation of diverse materials and the advancement of various 3D printing methods, such as Material Extrusion, Power Bed Fusion, and Vat-photo-polymerization [1-3]. Among these, Fused Deposition Modeling (FDM) stands out as the most widely utilized technique because of its straightforward operation, economic efficiency, and versatility. In the FDM process, thermoplastic filaments are continuously fed into a heated nozzle, where they are melted and deposited layer by layer to construct 3D objects. Popular materials employed in this technique include ABS, PLA, PETG, and TPU. PLA is widely utilized due to its biosafety and non-cytotoxic nature, making it an appropriate choice for tissue engineering applications. The process begins with a virtual 3D model, which is sliced into two-dimensional (2D) layers according to the desired resolution. These layers are converted into machine-readable instructions using Computer-Aided Design (CAD) software, enabling the sequential deposition of material onto a movable build platform. FDM technology, originally developed by Stratasys Corporation in the 1990s, has experienced significant advancement after the expiration of its patents in 2009. Today, it is widely applied across diverse industries, including aerospace, automotive, healthcare, and electronics. The ability of FDM to fabricate intricate geometries has rendered it essential for the production of

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tailored prosthetic devices, individualized medical instruments, and rapid prototyping applications. Additionally, its cost efficiency and reduced material waste have cemented its role as a disruptive force in modern manufacturing [4-9].

Despite its many advantages, FDM is not without limitations. Challenges such as suboptimal mechanical properties, inadequate surface finish, and low dimensional accuracy restrict its broader application. Dimensional accuracy is particularly critical in fields like tissue engineering, where precise fabrication is essential to meet individual requirements and ensure functional efficacy [10-14]. The dimensional integrity and other properties of printed parts are influenced by several process parameters. Identifying and optimizing these parameters is crucial for achieving high-quality, accurate products. Reaching a comprehensive decision is challenging, as it first requires identifying which dimension is most critical for analysis. Depending on the intended use of the product, dimensional accuracy may be crucial in one direction while being less significant in others [15-17]. Furthermore, if all dimensions are to be evaluated, a key question arises: how can a balance be achieved among them to arrive at a unified solution?

Many studies have not focused solely on the effect of printing parameters on dimensional accuracy; most have primarily concentrated on physical and mechanical properties, with some addressing dimensional accuracy as a secondary aspect [18-20]. Dey and Yodo [21] conducted a comprehensive review of the impact of different printing factors on mechanical properties and dimensional precision. They identified layer height and nozzle temperature as critical factors affecting accuracy. Their findings suggest that lower layer height and printing temperature are preferable for minimizing dimensional errors. Additionally, they observed shrinkage along the X and Y axes and expansion along the Z axis, highlighting the need for further investigation into build orientation as a significant parameter. Alafaghani and Qattawi [22] analyzed the influence of four fabrication variables on the mechanical strength and dimensional precision of PLA components. A balance was identified between achieving optimal mechanical strength and dimensional accuracy, with recommendations for using lower layer heights, reduced infill densities, and nozzle temperatures, along with a hexagonal infill pattern, to minimize dimensional deviations. In a similar study, Cardoso et al. [23] investigated the impact of printing speed, layer height, and raster angle on the mechanical strength and dimensional accuracy of PLA components. Their findings indicated that all these factors and their interactions play a crucial role in influencing dimensional inaccuracies.

Additionally, some researchers have explored the economic aspects of additive manufacturing, such as production time and cost, alongside dimensional accuracy. Enemuoh et al. [24] studied the impact of five process parameters, including shell thickness, layer thickness, printing speed, infill pattern, and infill density, on production metrics like component weight, manufacturing duration, and dimensional precision. Their results showed that outer layer thickness had the greatest influence on dimensions, followed by layer thickness, while other parameters had negligible effects. Haghighi and Li [25] studied dimensional accuracy alongside production costs, concluding that lower infill density reduces both costs and dimensional deviations across all axes. There are only a few studies specifically focused on dimensional accuracy, examining the impact of printing parameters and methods for optimizing it. Mohamed et al. [26] analyzed studies on the geometrical precision of FDM components and concluded that layer thickness and manufacturing angle are the most influential parameters. They noted that a lower layer height reduces dimensional errors. Shrinkage was observed along the length and width, while the measured thickness exceeded the intended values. Li et al. [27] investigated the effects of the rate of printing and layer thickness on surface deformation in PLA components, concluding that greater layer thickness and faster extrusion speeds lead to reduced warpage. Similarly, Galetto et al. [28] analyzed six process parameters affecting the quality of FDM parts, emphasizing the importance of part design features. For instance, low printing speed minimizes dimensional errors in overhangs, while higher speeds are more suitable for bridges. Frunzaverde et al. [29] evaluated the effect of nozzle temperature on the dimensional precision of natural and black PLA, finding that elevated temperatures result in greater dimensional inaccuracies, with black PLA exhibiting greater overall precision. Potnis et al. [30] applied Artificial intelligence (AI) modeling to enhance surface finish and dimensional precision, analyzing a wide range of printing variables. Garg et al. [31] focused on the dimensional accuracy, surface roughness, and hardness of ABS parts, using multi-objective optimization. They concluded that part orientation significantly impacts both dimensional accuracy and surface roughness, with 90° orientation being optimal.

This study aims to examine the effects of printing parameters bed temperature, nozzle temperature, nozzle diameter, print speed, infill density, infill angle, and layer height on the dimensional accuracy of a geometrically complex part, such as a screw and nut, along the length, width, and height axes. This analysis seeks to distinguish these parameters' influence on overall and detailed dimensional characteristics.

2. Experimental

In the present study, which aims to investigate the parameters influencing the dimensional accuracy of 3D-printed parts, various factors present during the printing process that can impact the final properties of the printed components are considered. Using a design of experiments (DOE) approach and an L8 orthogonal array, the effects of seven selected parameters at two levels on the dimensional accuracy of the printed parts were evaluated. The chosen variables include print speed, bed temperature, nozzle temperature, infill angle, layer height, infill density, and nozzle diameter. The printing conditions for the eight prepared samples, based on the selected factor levels, are detailed in Table 1 and were systematically analyzed.

The screw and nut selected for printing in this study are of significant importance. In addition to overall dimensional features such as the length and diameter of the screw and nut, finer dimensional details, including the dimensions and uniformity of the threads and the ability of the two parts to fit together securely, are also significant. Figure 1 shows a schematic image and the dimensions of the model sample.

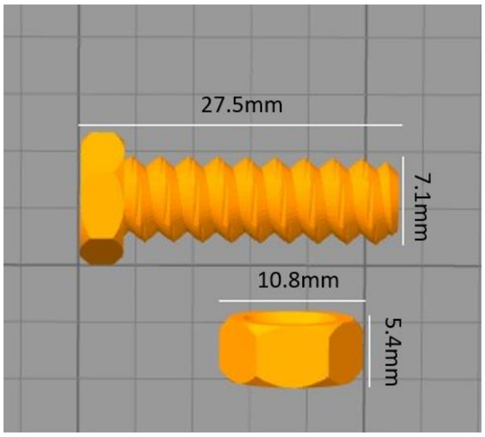


Figure 1: Schematic image and the dimensions of the model sample.

Table 1: Factors analyzed and their selected levels (L8 orthogonal array).

Factors	Print speed (mm/min)	Bed temperature (°C)	Nozzle temperature (°C)	Infill angle	Layer height (mm)	Infill density	Nozzle diameter (mm)
Code	A	B	C	D	E	F	G
1	70	65	220	45-45	0.15	20	0.6
2	30	65	220	0-90	0.45	20	0.4
3	70	55	220	0-90	0.15	80	0.4
4	30	55	220	45-45	0.45	80	0.6
5	70	65	195	45-45	0.45	80	0.4
6	30	65	195	0-90	0.15	80	0.6
7	70	55	195	0-90	0.45	20	0.6
8	30	55	195	45-45	0.15	20	0.4

The parts were printed using black PLA filament with a 1.75 ± 0.05 mm diameter, utilizing an FDM 3D printing machine, Datis Pro. All prints were performed under identical temperature/humidity conditions. The constant settings for printing are presented in Table 2.

3. Results and Discussion

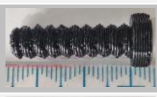
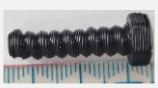
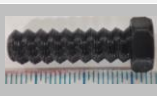
Table 3 provides images of the printed screws and nuts, highlighting the surface quality and tightening performance. The results demonstrate that printing parameters significantly influence the appearance and functional characteristics of the printed components. Specifically, samples printed with a layer thickness of 0.15 mm (samples 1, 3, 6, and 8) exhibit a better surface quality than those printed with a layer thickness of 0.45 mm. Similarly, these samples generally show better-tightening performance. However, the sub-optimal performance of samples 1 and 6 (printed with a larger nozzle diameter suggests that factors other than layer thickness also play a critical role in determining this property. Moreover, parts printed at a bed temperature of 65°C (samples 3, 4, 7, and 8) demonstrate improved quality compared to those printed at 55°C. While other factors do not show a significant standalone impact, their interactions with key parameters appear to influence the outcomes.

Table 4 presents the length and diameter of the printed screws and nuts as two overall dimensional characteristics of the printed parts. The data demonstrate that changes in the levels of the selected factors significantly influence the properties of the printed parts. The effects of the factors on the overall dimensional characteristics studied are highly dispersed, making it challenging to attribute a direct impact to any single factor. This suggests that factor interactions play a decisive role, with their influence varying based on the specific dimensional characteristic under consideration (e.g., width or depth) and changing according to the size, complexity, and details of the printed part.

Table 2: Constant process parameters for PLA nuts and screws.

Process Parameter	Value
Nozzle diameter	0.4
Extrusion multiplier	0.92
Extrusion width	0.45
Infill Pattern	Rectilinear

Table 3: Images of printed screws and nuts with appearance and tightening performance.

Sample	Printed Screw	Screw Appearance	Printed Nut	Nut Appearance	Screw and Nut tightening
1		Good		Fairly good	Fairly good
2		Bad		Not Bad	Bad
3		Good		Fairly good	Good
4		Fairly good		Fairly good	Bad
5		Bad		Bad	Bad
6		Good		Good	Fairly good
7		Fairly good		Not Bad	Bad
8		Good		Good	Good

Therefore, the importance of employing experimental design methods, such as Taguchi's approach, to analyze the effects of various parameters and identify optimal conditions in the 3D printing process is emphasized, as single-factor analysis methods cannot account for interactions, and full factorial methods require an impractically large number of experiments [32,33].

Table 5 presents the calculated averages from four measurements for each response at the same factor levels. Figures 2 to 5 depict the influence of each factor on the diameter of the screw, length of the screw, diameter of the nut, and height of the nut. A comprehensive analysis of these figures clearly illustrates the differential impact of each factor on the dimensional characteristics of the printed parts.

As shown in Figure 2, three parameters—infill angle, infill density, and layer height—had minimal to no significant effect on the diameter of the printed screws. Conversely, increasing the nozzle diameter and print speed resulted in a smaller screw diameter, while lower bed and nozzle temperatures led to a reduction in the printed screw diameter. It can be concluded that the impact of these factors on the printed part's dimensions is closely linked to the degree of melt shrinkage during cooling and solidification [34-36] and also to processing limitation in 3D printing.

Table 4: Length and diameter of the printed screws and nuts as dimensional characteristics of the printed parts.

Sample	Nut diameter (mm)	Nut height (mm)	Screw diameter (mm)	Screw length (mm)
1	10.06	5.31	6.82	27.72
2	10.63	5.47	7.34	27.30
3	9.83	5.01	7.02	27.69
4	10.85	5.34	7.00	27.64
5	10.70	5.49	6.97	27.53
6	10.46	5.41	7.05	27.65
7	10.54	5.30	6.51	27.56
8	9.69	7.00	5.10	27.65

Table 5: Effect of factors on the overall dimensions of the printed screw and nut.

Factor	Factor Level	Screw length (mm)	Screw diameter (mm)	Nut height (mm)	Nut diameter (mm)
Infill angle	+	27.550	6.980	5.298	10.365
	–	27.635	6.948	5.310	10.325
Infill density	+	27.628	7.010	5.313	10.460
	–	27.558	6.918	5.295	10.230
Nozzle diameter (mm)	+	27.643	6.845	5.340	10.478
	–	27.543	7.083	5.268	10.213
Layer height (mm)	+	27.508	6.955	5.400	10.680
	–	27.678	6.973	5.208	10.010
Print speed (mm/min)	+	27.625	6.830	5.278	10.283
	–	27.560	7.098	5.330	10.408
Bed temperature (˚C)	+	27.550	7.045	5.420	10.463
	–	27.635	6.883	5.188	10.228
Nozzle temperature (˚C)	+	27.588	7.045	5.283	10.343
	–	27.598	6.883	5.325	10.348

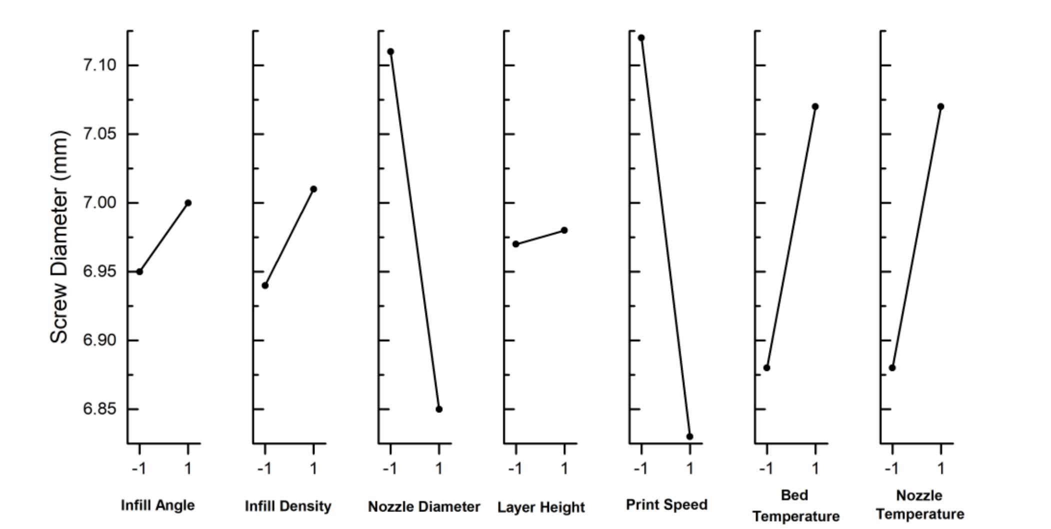


Figure 2: Effect of process parameters on screw diameters.

In other words, factors with a greater influence on shrinkage lead to more noticeable changes in the dimensional characteristics of the printed part [26, 27]. In additive manufacturing, shrinkage is controlled by some key factors, such as the degree and intensity of orientation of polymer chains in the molten state and during exit from the die, the cooling rate of the molten polymer, and its crystallization behavior during solidification. The extent of each parameter's impact depends on its effect on these factors. The maximum observed variation in the screw diameter, resulting from the selected factors and their levels, was 4%. This value is calculated based on the ratio of the largest observed difference by a changing in level of a factor (here print speed) to the mean value.

Figure 3 illustrates the impact of the studied factors on the length of the printed screw. The maximum observed variation is less than 1% of screw length, indicating that this dimensional characteristic is less affected by the factors. Nevertheless, as expected, layer height shows the most significant influence, while the other parameters exhibit relatively similar levels of effect.

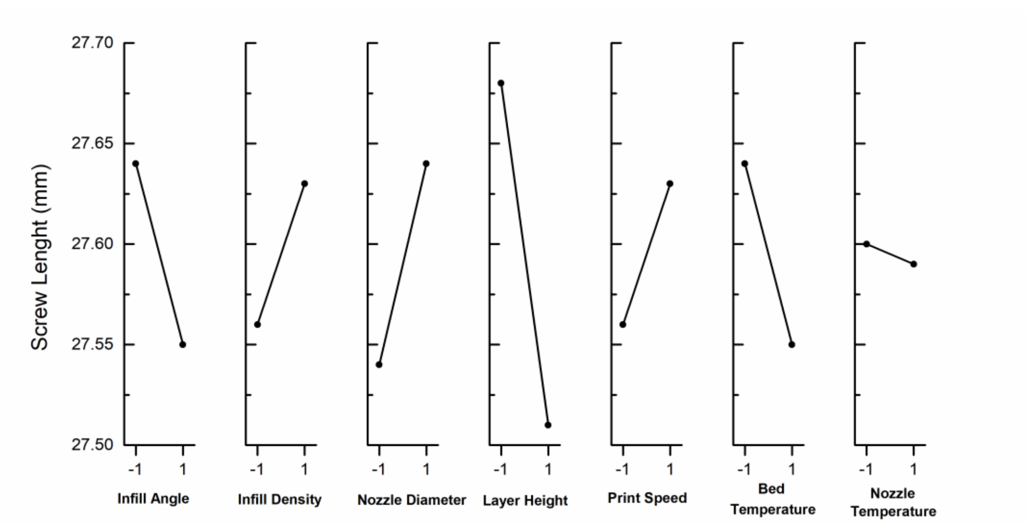


Figure 3: Effect of process parameters on screw length.

Figures 4 and 5 illustrate the effects of the studied factors on the height and diameter of the printed nut. As shown in Figure 4, the two parameters with the most significant influence on the nut height are layer height and bed temperature, while other factors showed negligible effects. The average impact of changing the level of these two factors on nut height is approximately 4 %. An increase in layer height and bed temperature increases nut height, likely due to a decrease in melt shrinkage during crystallization.

As depicted in Figure 5, the layer height is again the most influential factor regarding the nut diameter, causing a change of approximately 7 % in the printed nut diameter.

In Table 6, the average dimensions of the printed parts are shown in comparison with the dimensions of the model, as it can be seen that the dimensional error observed for screws and nuts is positive in the transverse direction and negative in the height (depth) direction of the parts. This difference indicates that the amount of shrinkage is a function of the direction and the amount of error also varies for two parts with different dimensions and details.

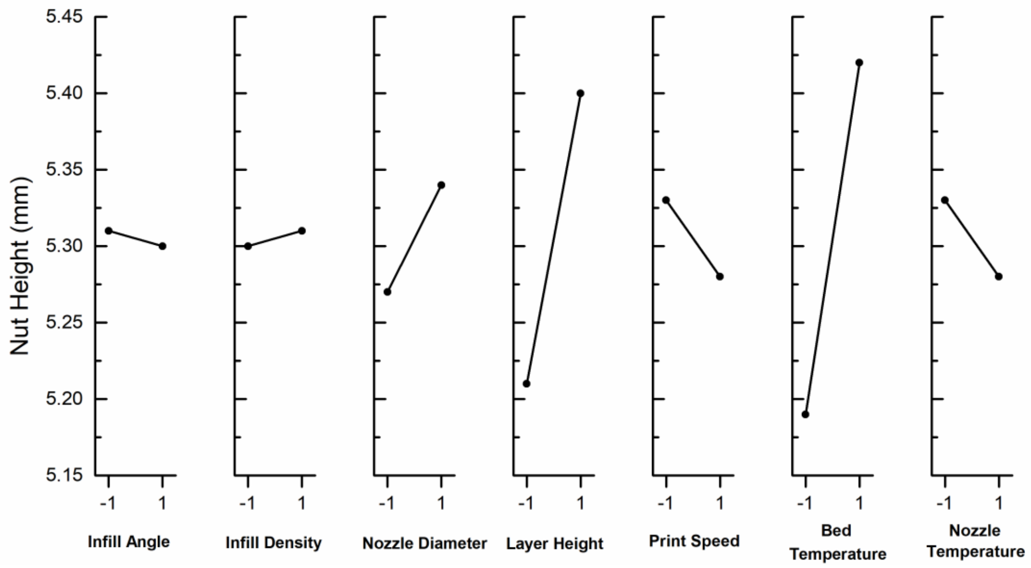


Figure 4*:* Effect of process parameters on nut height.

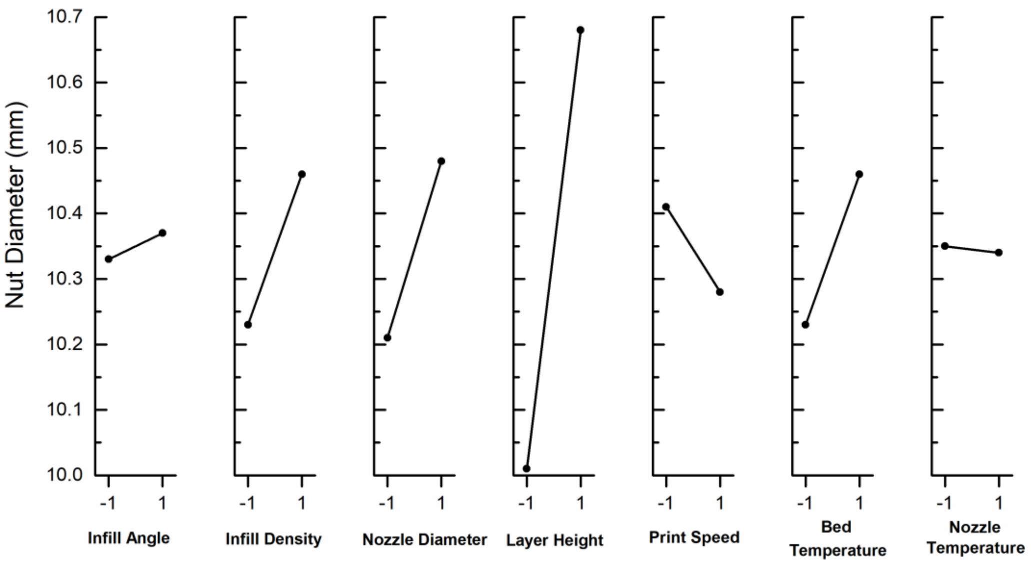


Figure 5: Effect of process parameters on nut diameter.

Table 6: Average dimensions of the printed parts in comparison with the model.

Factor	Average printed size (mm)	Model size (mm)	% Error
Screw Diameter	6.96	7.10	-1.97
Screw Length	27.59	27.50	0.33
Nut Height	5.30	5.40	1.90
Nut Diameter	10.35	10.80	-4.17

4. Conclusion

This study demonstrates printing parameters' significant influence and interactions on the dimensional accuracy of geometrically complex parts fabricated using FDM. The findings reveal that layer height, nozzle diameter, and bed temperature are the most influential parameters, with their effects varying based on the part's dimensional characteristics and geometric complexity. Dimensional errors were observed to be direction-dependent, with positive errors in the transverse direction and negative errors in height, highlighting the anisotropic behavior of the FDM process. Factor interactions played a crucial role in determining dimensional accuracy, emphasizing the importance of employing experimental design methods, such as Taguchi's approach, to identify optimal parameter settings efficiently. The maximum dimensional deviations observed were 4 % for screw diameters and 7 % for nut diameters, indicating the need for further optimization to meet high-precision requirements. These results contribute to a deeper understanding of the process-parameter relationships in FDM and provide a foundation for improving the accuracy and reliability of fabricating complex 3D-printed components. Future research should focus on exploring additional geometries, materials, and advanced optimization techniques to enhance dimensional accuracy further. Also, it is necessary to consider on the cost of producing a part (printing time and mass of the printed part) and the desired mechanical properties of printed part along with its dimensional accuracy.

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