Designing a Visuohaptic Simulation to Promote Graphical Representations and Conceptual Understanding of Structural Analysis

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***Abstract*— Structural analysis is a foundational statics concept for students majoring in mechanical engineering, civil engineering, and engineering technology, among others. However, the mathematical emphasis of a typical statics courses lies in algebraic calculations, matrices, vectors, and sometimes de-emphasizes student understanding of the behavior of the overall structure as a system, focusing instead on its individual elements. This study investigates students' conceptual understanding of forces acting and reacting in a truss structure as well as their corresponding representations in the form of Free Body Diagrams (FBDs). Our findings suggest that students primarily demonstrated partially coherent answers suggesting that they may hold some misconceptions about truss behavior. The most prevalent error was that students failed to account for the mutual (equal and opposite) forces between connected bodies that were separated for analysis. Based on our findings we propose the design of a learning experience that combines principles of embodied learning with the affordances of visuohaptic simulations to address students' misconceptions.**

Keywords— conceptual understanding; graphical representations; statics; trusses; visuohaptic simulations.

I. Introduction

Research suggests that there is a beneficial synergy between conceptual understanding and graphical representations [1]. Specifically, graphical representations can help students to gain insight into the material world [2], identify relationships between components of a system [3], and provide potential for new solutions to a problem [4]. In educational settings, however, research has struggled to show effective ways of using representations meaningfully [5, 6] as overall, student representational proficiencies are unsatisfactory [5, 7]. This is also the case for difficult concepts in engineering. We focus in this paper on the statics domain, where some students, even after instruction, still struggle to make proper representations of forces using free body diagrams (FBDs), and cannot demonstrate overall conceptual understanding [8].

Structural analysis is a foundational statics concept for students majoring in mechanical engineering, civil engineering and engineering technology, among others. However, the mathematical emphasis of a typical statics courses lies in algebraic calculations, matrices, vectors, and sometimes does not sufficiently reinforce students' overall understanding of the structural system [9]. Developing such skills is critical for engineers because it is useful during the early design stages, where qualitative decisions can quickly eliminate unworkable designs and instead devote resources to practical and efficient possibilities [10]. Furthermore, students need to develop an ability to connect their intuition to the solution of more complex design problems. Even though multiple strategies including laboratory-based experiences, and simulation-based learning materials have been developed to promote students' conceptual understanding of trusses [9, 11-13], it is still not clear what is the best approach.

This study investigates students' conceptual understanding of forces acting in a truss structure, as well as their representational competence of FBDs. Based on our findings we propose the use of visuohaptic simulations for teaching statics concepts that combines the affordances of simulations and of physical laboratories for learning. We have developed a visuohaptic simulator that allows interaction and haptic feedback on several truss structures. By using our system, we attempt to answer the following specific research question

1. What are students' graphical representations and conceptual understandings of the forces acting on a truss structure?

To answer this research question we evaluated the coherence between the forces acting on the trusses members and the forces exerted by the joints members to maintain the structure in equilibrium. Also, we evaluated the forces exerted by the support of the structure to the wall. Once identified students' misconceptions, we propose the design of a visuohaptic simulation to help students to correct their knowledge.

II. Methods

This study investigates students' conceptual understanding of forces acting in truss structures and the corresponding representations FBDs after being exposed to formal in-class instruction. Our goal was to identify how embodied learning could guide the design of an educational intervention that could help students improve conceptual understanding and representational competence of truss structures using visuohaptic simulations

A. Participants and Procedures

Participants included 37 undergraduate students from an Engineering Technology course from a Midwest University. Students self-reported as 67.5% sophomore, 16.2% junior, and 16.2% did not reported. Twenty-three of the participants were male and 14 were female. Participants listened to a lecture that introduced the topic of trusses, then they completed a pre-assessment of their knowledge about trusses.

B. Assessment

The questions on the assessment were based on a simple truss structure with three joints and members. An applied force acted on Joint B in three different configurations. Fig. 1 shows the truss structure and the configurations of the applied force.

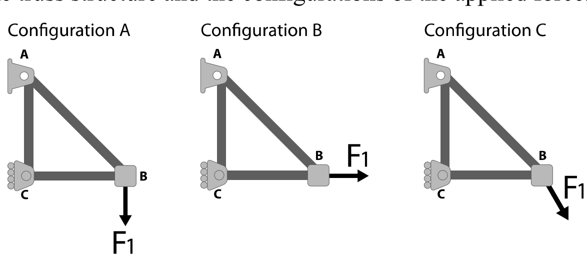


Fig. 1. Truss structure and configurations of the external force.

As show in Fig. 1, configuration A had an applied force acting on the y-negative axis, configuration B had an applied force acting on x-positive direction, configuration C had an applied force acting 60 degrees below the horizontal plane.

For each configuration, participants answered verbal and representational questions. In the verbal questions, participants determined what members, AB, BC and AC, were under tension, compression or were zero-force members. In the representational questions, participants were prompted to draw the corresponding free body diagrams (FBDs) for each joint (A, B and C), and for each configuration. Fig. 2 shows an example of the FBDs of participant ID3. It is important to notice that we are evaluating the coherence in students' answer. Only the mathematical solution will help to accurately determine the forces acting on a member, but here, we are analyzing if students are able to coherently determine the direction of the forces exerted by the joint when the members are under compression, tension or are zero-force members.

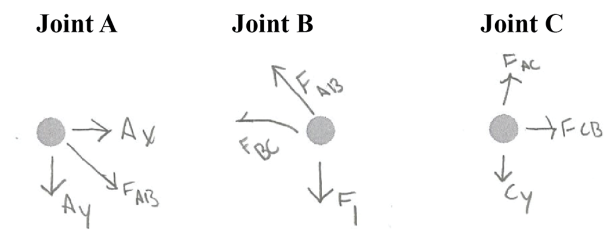


Fig 2. Sample of FBDs of the joints for a particular configuration (student ID3)

C. Data Analysis

To approach our research question we jointly analyzed students' conceptual answers and their corresponding FBD by recreating the drawings compiling forces acting on corresponding joints and members (e.g., Fig. 3). For example, answers from participant ID3 is presented in Fig. 3 below.

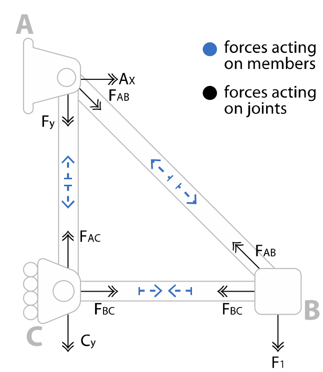


Fig 3. Compilation of the student ID3-visuohaptic simulation answers.

As shown in Fig. 3, participant ID3 indicated that member AB was under tension, member AC under tension, and member CB under compression. Participant ID3 provided a coherent answer identifying the direction of the forces in the member AB and the forces exerted by the joint A and joint B on the member AB, that is, forces were acting in opposite directions. The participant ID3, also drew the forces coherently between Joint A and Joint C and the member AC. The participant ID3, did not identify a coherent response by noting the direction of the forces acting on the member CB and its relationship with the joint B and C. That is, the forces acting on the joint and the member were shown as acting in the same direction.

Once we recreated each of the drawings from each participant, we identified seven main characteristics on participants' answers. Table 1 shows the main characteristics found in the assessment answers.

Table I. Coding of participants' answers from the assessment.

Characteristic	Type
Incorrect FBD – Joint A	Error 1
Incorrect FBD – Joint B	Error 2
Incorrect FBD – Joint C	Error 3
Forces in the joints and members are not opposite (not coherence joint-member)	Error 4
Not coherence between the direction of the forces in the joints	Error 5
Forces in the joints and members are opposite (coherence joint-member)	Success 1
Coherence between the direction of the forces on the joints	Success 2

As shown in Table I, some characteristics of students' responses and diagrams were correct, and others were incorrect. Incorrect FBD referred to responses that incorrectly identified the direction of the force acting on the joint or missing forces acting on the joint. Incoherence between the direction of the forces on the members and joints was also identified as an error. That is, answers were considered incorrect when participants indicated that the forces acting on the joint followed the same direction as the forces acting on the members. In this case the forces could not be cancelled, and the system would not have been in equilibrium. Incoherence between the directions of the forces in the joints meant that the forces were not acting in the opposite direction. Figure 4a shows a correct answer for this configuration, and Figure 4b shows the answer from participant ID6 with the errors highlighted.

Figure 4a (correct) Figure 4b

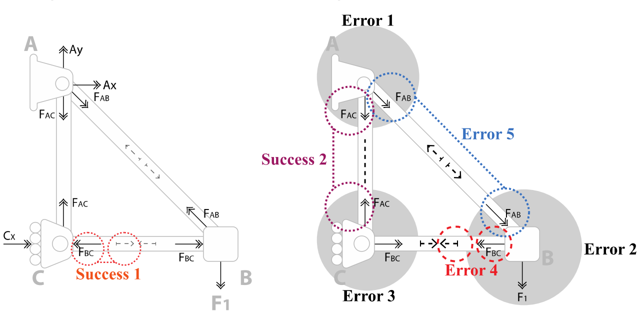


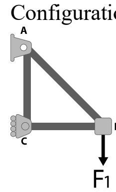
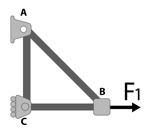
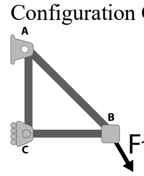
Fig 4. Characteristics of the answer of participant ID6.

As shown in Figure 4b, participant ID6 had all the errors in their answer. The FBDs were scored as incorrect because the participant did not include all the forces acting on the joint. In the case of the FBD-joint B (Fig. 4b), the answer included all forces, but it was still counted as incorrect because the forces in the joint are not opposite to the forces of the member (error 4). The error 5 is shown in the AB member on Fig. 4b, where both forces were shown acting downwards. Success 1 was shown in the member AC where the joint forces were shown acting on opposite direction. Success 1 is illustrated in the correct answer (Fig. 4a), where the force acting in the member is acting in the opposite direction to the force exerted by the joint.

III. Results

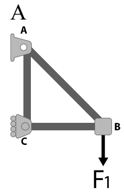
Participants had difficulties drawing the FBD of the joints. Table II shows the frequency of students with incorrect FBD on each configuration.

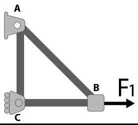
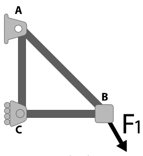
Table II. Incorrect FBD of the joints on each configuration

Configuration	FBD	number of students with incorrect joint FBD (n=37)
Configuration A 	FBD-joint A	32 (86.49%)
	FBD-joint B	28 (75.68%)
	FBD-joint C	30 (81.08%)
Configuration B 	FBD-joint A	31 (83.78%)
	FBD-joint B	26 (70.27%)
	FBD-joint C	30 (81.08%)
Configuration C 	FBD-joint A	33 (89.19%))
	FBD-joint B	24 (64.86%)
	FBD-joint C	32(86.49%))

As shown in Table II, most of the students incorrectly drew the FBDs of the joints. Joint A and Joint C had higher percentages of incorrect answers due the incorrect modeling of the reaction forces at pin A and roller C. Specifically, all the students that had incorrectly drawn the FBD-joint A is because omit the forces or drew incorrectly the direction of the forces acting on Joint A. For the FBD-joint C, including all the configurations, 2 participants drew correctly the reactive force Cx, 4 participants drew incorrectly the FBD-joint C but drew correctly the reactive force Cx, and 9 participants drew incorrectly the FBD-joint C and drew incorrectly the reactive force Cx. Fig 4a shows the correct direction of the reactive force Cx and the participant ID6 not including the force on the FBD.

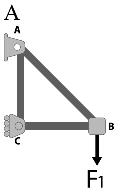
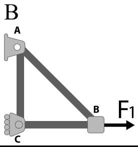
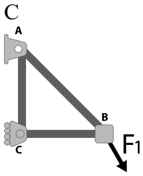
Table III. Errors in students' conceptual understandings.

Conf.	Error type	number of students with errors (n=37)
A 	Error 4 (joint-member)	25 (67.57%)
	Error 5 (joint-joint)	16 (43.24%)

B 	Error 4 (joint-member)	21 (56.75%)
	Error 5 (joint-joint)	18 (48.65%)
C 	Error 4 (joint-member)	26 (70.27%)
	Error 5 (joint-joint)	19 (51.35%)

Participants also displayed lapses in conceptual understanding [14]. Incoherence among the forces acting on the joints and the members (error 4) and among the joints (error 5) is presented in Table III. Error 4 was more frequent than error 5. That is, participants tended to draw the forces acting on the joints in the same direction as the member (not opposite). Table V presents the number and percentage of participants that showed successful characteristics in their responses.

Table V. Successes in students' conceptual understandings.

Conf.	**Success type**	**number of students with successes (n=37)**
A 	Success 1 (joint-member)	22 (59.46%)
	Success 2 (joint-joint)	17 (45.95%)
B 	Success 1 (joint-member)	23 (85.18%)
	Success 2 (joint-joint)	21 (56.75%)
C 	Success 1 (joint-member)	19 (51.35%)
	Success 2 (joint-joint)	21 (56.75%)

Opposite to the incoherence errors, responses showing successful characteristics correctly and coherently identified active and reactive forces in the FBD. As shown in Table V, the success 1, considering the direction of the forces acting on the member and exerted by the joint was more common than success 2 (except for the configuration C).

IV. Discussion

Fig 5 shows a summary of our findings. As shown in Fig 5, the partially coherent answers and not coherent answers were more frequent that the coherent answers, suggesting that students may have some fragmented understanding, also called "conceptual lapses" [14]. In most of the cases these fragmented ideas were attributed to students' inability to consistently draw the forces exerted by the joints for a given applied force. These findings suggest that participants had difficulties in coherently determine the direction of the force acting on the joints and members of a truss structure. As a consequence, participants were not able to set up and consider all reacting forces on members connected to a specific joint. Failing to consider all the acting forces may result in common errors identified in this study (Error, 1, 2, 3) among participants. Furthermore, participants had difficulties in considering the reactions as a force contrary to an acting force. This could be a result of students' difficulty on mastering physics concepts [18]. Participant's difficulties in failing to account for the relationship of reacting forces with elements that are connected are similar to the errors suggested by Steif [8]. Prior studies also document students' struggle to identify the real forces, component and resultant of forces [15, 24]. These difficulties arise from students' inability to understand the relationship between Newton's laws and the magnitude and direction (Error 5) of the vectors represented in the free body diagram [16]. Interestingly, this study's findings suggest that participants had less percentage of error in cases, such as Joint C, where the force is coherent between joints and members (Success 1). Simultaneously, the percentage of error is less when the direction of the forces is coherent among joints (Success 2) for the case of Joint A.

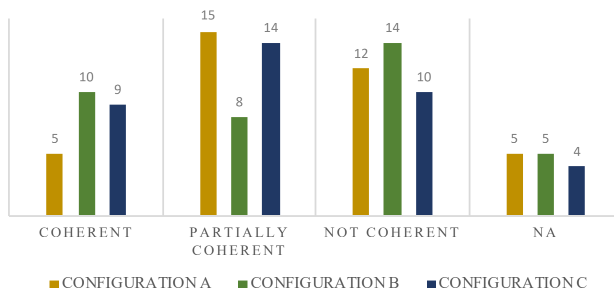


Fig 5. Categorization of students' answers.

V. Implications for Learning

Facing the challenge of teaching and learning about abstract and non-visible concepts such as forces, statics instruction has evolved and followed many of the modern trends observable in other classes including using hands-on experiments and physical manipulatives [17, 25, 26]. Particularly in engineering education, the laboratory experience becomes a relevant component for reinforcing conceptual understandings gained during lecture [18]. To this end, we propose the use of visuohaptic simulations as a potential solution that combines the affordances of simulations for learning with hands-on experience. This proposition is also grounded in theories of embodied learning which argue that knowledge partially relies on neural mechanisms pertaining to sensory and motoric processes [19]. Thus, this theory argues that cognitive processes develop when learning emerges from real-time, goal-directed interactions between organisms and their environment. Furthermore, theories of embodied cognition maintain that brain regions located in the sensorimotor cortex and nearby association cortex play a prominent role in information processing and information retrieval. These same brain regions are also responsive to information within a specific sensory modality responsible for representing the properties of a given object [19]. The implications of this theory pertaining to learning of abstract concepts in engineering, is that concepts are organized based on properties and properties are dependent on specific sensory modalities corresponding with one's physiology and environment [20]. That is, abstract scientific concepts are comprehended based on embodied visuospatial representations [21]. We therefore believe that visuohaptic simulations can be a viable solution to help students overcome their fragmented ideas.

A. *The visuohaptic simulation design*

The design of the visuohaptic simulation followed principles of multimedia for learning [22]. The simulation was implemented in C++ using modern OpenGL to visualize the 3D scene and to provide visual cues such as shadows and cross-hair cursors. Students could interact and receive force feedback through a Novint Falcon haptic device. We used Chai3D API to synchronize the simulation with the haptic device. The Novint Falcon haptic device provides up to 10 N of force feedback within an area of 10x10x10 cm. Fig. 6 shows a screenshot of the simple truss structure implemented in Chai 3D.

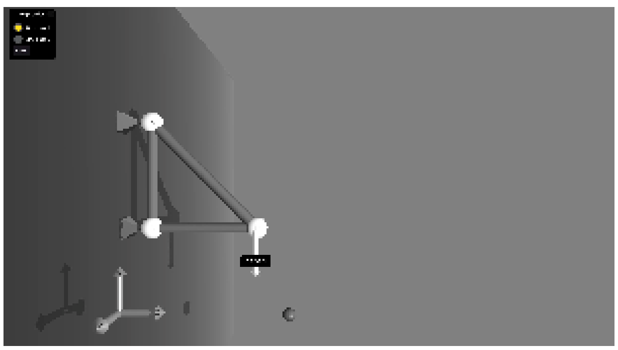


Fig 6. Configuration A implemented in the visuohaptic simulation

Each scenario allowed students to:

1. Apply up to three forces in the joints to see the effect in the structure.
2. Identify members in compression
3. Identify member in tension
4. Identify zero force members
5. Identify the direction of the forces exerted by the joints (FBD).

B. *Instructional overlay*

The learning intervention followed principles of embodied learning as proposed by Abrahamson and Lindgren [23]. According to Abrahamson and Lindgren, to design for embodied learning requires that *activities* are designed so that students use perceptual senses and kinesthetic coordination to perform new actions. The tasks, at the beginning, should include little to no symbolic stimuli, and move from simple tasks to more complex ones. Abrahamson and Lindgren also recommend that the *materials* should include technological artifacts facilitated by instructors. The materials should allow for some physical movement ranging from one single finger to whole-body movement. And for the case of simulations, students should experience first-hand manipulation. Students, in the process, may need scaffolding to effectively engage with the learning materials.

Visuohaptic simulations in general can engage students in hands-on learning experiences via two types of feedback, visual and tactile. The design of the proposed visuohaptic simulation included a simple truss structure and a more complex truss structure. First, students solved the simple truss structure and then the more complex truss structure. In addition, facilitation was provided by the instructor and guidance through a laboratory worksheet.

C. *Interacting with the visuohaptic simulation*

Students interacted with the simulation using two senses: sight and touch. The simulation had visual cues that allowed students to visually identify forces and effects on the structure. Haptic devices provided tactile feedback that allowed students to feel the acting forces on the structure. Once students launched the simulation, the simple truss structure appeared (structure 1). To apply a force on a joint, the user positioned the haptic cursor on the joint, pressed the button located on the haptic device, and pulled down (in the case of Configuration A), or to any direction (for other force configurations) to set the applied force. Fig 7 shows the interaction to apply a force on a joint.

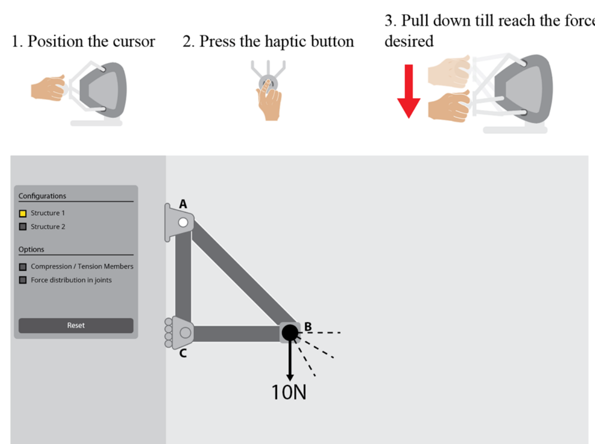


Fig 7. Setting an applied force of 10N on Joint B.

The applied force could have different magnitudes, for example, of 2N, 4N, 6N, 8N or 10N. The direction of the force could be in the x-positive axis, 30 degrees below the x-positive axis, 60 degrees below the x-positive axis or in the y-negative axis. Once the applied force was located, the user could feel the forces acting on the members. To identify if the forces of the members were in tension, compression or the member was not distributing forces (zero force member), the user interacted with the member along its length, as described next.

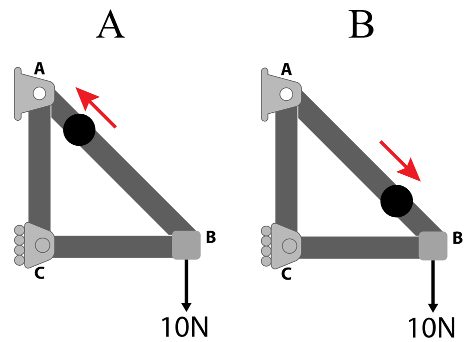


Fig 8. AB member under tension.

As shown in Fig. 8, when the users located the haptic cursor anywhere along the member and presses the button on the haptic device, the device would move the cursor either toward the center of the member or toward one of the joints, depending on whether the member was in tension or compression. For members in tension (Fig. 8) the cursor moved toward the joints, while for members in compression (Fig. 9) the cursor moved toward the member's center.

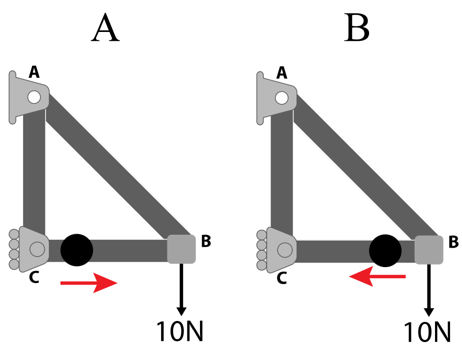


Fig 9. CB member under compression.

If, when the button on the device was pressed, the haptic device would not move, that would be interpreted as the member having a zero force. The visual cues that could also help students to identify the forces acting on the members are shown in Fig 10.

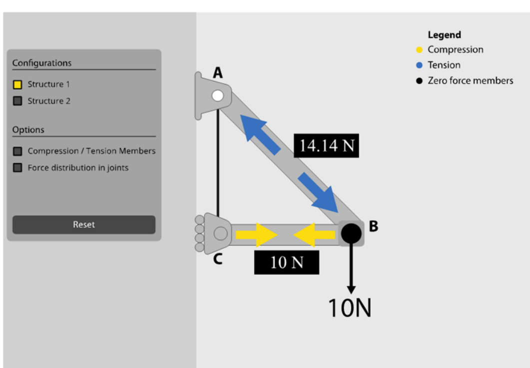


Fig 10. Visual cues

As shown in Fig 10, the arrows and the magnitude of the forces were shown once the user selected the visual cues. Visual cues and haptic feedback were available to participants at the same time. Students also interacted with a more complex truss structure (Fig. 11) in the same way as the simple truss structure.

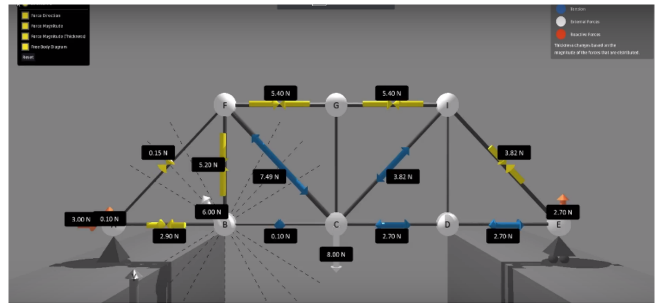


Fig 11. Screenshot of the visuohaptic simulation tool in visual mode on.

VI. Conclusion and Future Work

Reformative thinking of the embodied basis of cognition opens new possibilities for enhancing human learning in complex domains, such as those in STEM. Understanding learning in those complex domains and how those can be supported with technology, is an important step to effectively train STEM professionals. Specifically, new forms of human-technology interactions can now increase the amounts and types of information for a human to absorb and retain. Therefore, our future work will identify how students uptake information over a mix of one or more sensory modalities; our ultimate goal is to enhance human learning by launching traditionally unused cognitive pathways.

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