Assessments of Ultra-Low-Cost Venturi Nozzle in Undergraduate Engineering Classes

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1. Introduction:

The literature is full of articles indicating the limitations of traditional lecture-based instruction in reinforcing fundamentals and helping engineering students with their long-term conceptual understanding[1, 2]. Even so, professors at most engineering schools still cover fundamentals in the same lecture-based method that has been used for decades and shown not to be the best for students. Deficiencies in traditional teaching methods left employers of engineers with great demand for innovative pedagogies which improve students' teamwork skills and core understanding in problem-solving[3].

Among useful pedagogies are hands-on teaching methods which help learners to better understand concepts and derive interrelationships between principles through interactive learning strategies such as those presented by Kolb's experimental learning model[4]. In each discipline, hands-on experiences to which students are exposed, should closely mimic what students will encounter in the real-world after graduation. Toward this aim, real-world engineering systems in the form of Desktop Learning Modules (DLMs) have been developed[5, 6]. Incorporating such DLMs into classrooms allows students to observe, analyze and actively take part in integrating ideas, all of which have potential to reduce conceptual difficulties in students more so than a lecture-based teaching style[7].

The current, commercially available DLMs are expensive and could cost an institution tens of thousands of dollars to purchase and set up, making DLMs inaccessible to many students around the world. This has motivated us to design and manufacture ultra-low-cost DLMs that could be purchased at around the price of a textbook. To design such DLMs, which could be useful in reducing conceptual barriers, the first thing is to identify misconceptions the students maintain. In this paper we present our protocol for determining misconceptions related to the relationship between pressure and velocity through a contraction and expansion, the development of an ultra-low-cost venturi, our assessment technique which is based on Bloom's taxonomy, and an analysis of results to decide if using such an ultra-low-cost DLM can abate existing conceptual difficulties.

2. Methods

2.1. Identifying Misconceptions – Bernoulli's Principle

Fluid mechanics is one of the important fields of study in chemical and mechanical engineering because graduates will deal with fluids and the effects of forces on fluid motion many times during their careers. Because of the subject's importance and because it became clear to us that even students who completed a fluid mechanics course have difficulties in describing the true meaning of continuity and the relationship between flow work and kinetic energy in flow through varying cross sectional areas[8], we became persuaded we needed to rectify the knowledge gaps maintained after a lecture-based style of instruction by systematically incorporating hands-on learning strategies.

As shown in Figure 1 and alluded to earlier, identifying misconceptions should be the basis of any experimental learning model. Our group has previously identified some of persistent misconceptions by interviewing students who had completed a fluid mechanics and heat transfer class[8]. To make sure we are considering all misconceptions for the design of our ultra-low-cost venturi, we took advantage of the mini-Delphi model. In this model, a group of experts are asked for their input on a selected issue[9, 10]. Because face-to-face interviews eliminate misunderstandings and can be accomplished in a shorter period of time in comparison with electronic communication, we invited two professors from mechanical engineering and two professors from chemical engineering, all of whom have years of experience in teaching fluid mechanics courses, to meet and answer the following questions:

Question #1. What are the misconceptions you have seen students have when you are teaching Bernoulli's principle?

Question #2. Which misconceptions about Bernoulli's principle persist in students even after completing your class?

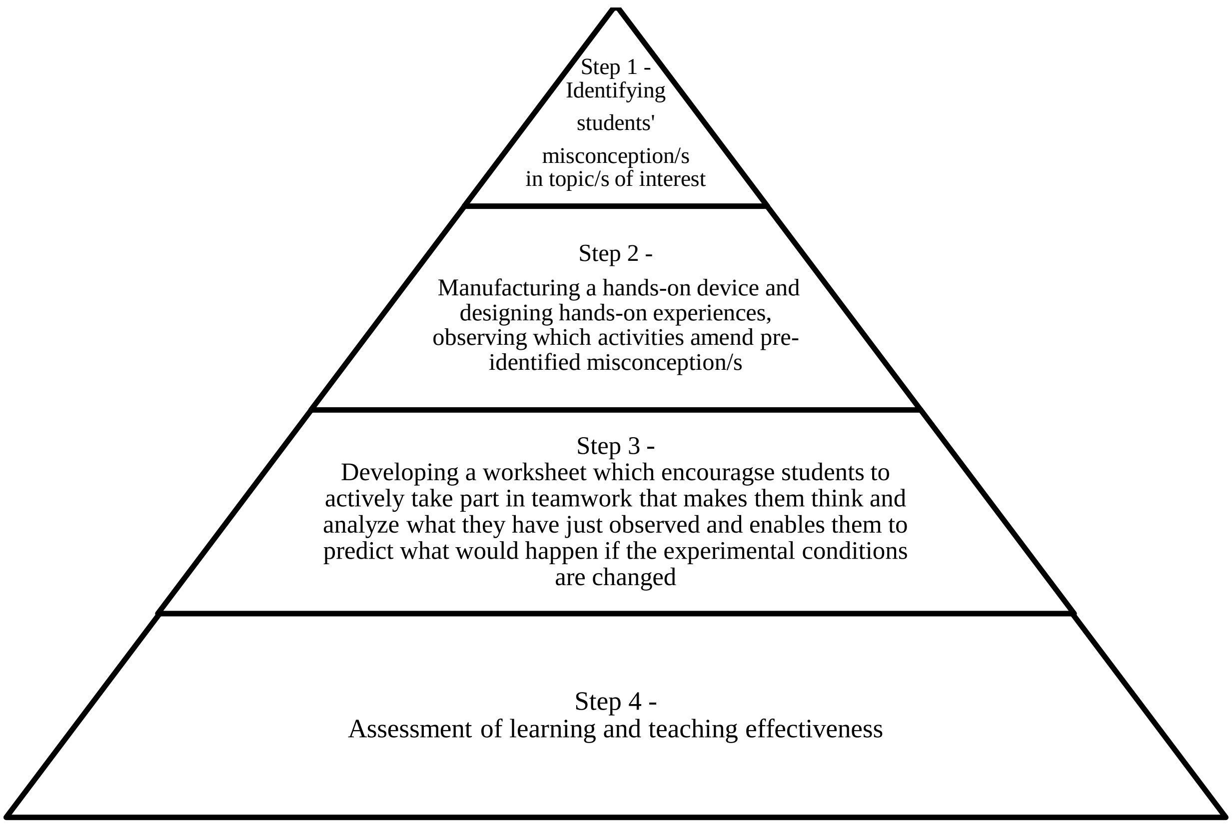


Figure 1. Step-by-step, systematic model for developing a hands-on experience

2.2. Ultra-Low-Cost Venturi Meter

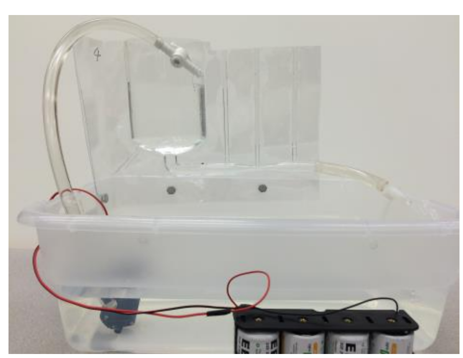


Figure 2. Ultra-Low-Cost Venturi

Bernoulli's principle relates the pressure of an ideal fluid (zero viscosity, constant density, and steady flow) to its elevation and speed. Based on input from our expert team members on common misconceptions in students' understanding of Bernoulli's principle and because a venturi meter provides a consistent means of demonstrating Bernoulli's principle, we designed and developed an ultra-low-cost venturi meter, a detailed description of which is in a companion paper presented at ASEE[11]. Briefly, to manufacture the venturi, first two halves of the nozzle were designed in SolidWorks and 3D printed in ABS plastic. Then using a vacuum forming machine and the two 3D printed molds, each half of the venturi was formed on a PETG thermoform plastic sheet. The two halves were fastened together using Weld-on 3 Scirip Acrylic glue (Figure 2). The whole venturi with all accessories including pump, batteries, etc. cost less than $50 to manufacture.

2.3. Assessment of Learning

It is well-known in the field that most engineering students consider equations as a fill in the blank formula without understanding what each term really means[12]. This lack of conceptual understanding of fundamentals makes it difficult for students to deal with new problems. However, dealing with new situations and applying a fundamental understanding of phenomena in new contexts are inseparable parts of engineering careers. As a result, proper assessment of learning regardless of teaching style is vital to engineering education.

We used pre-assessment and post-assessment models to check the efficacy of the ultra-low-cost venturi in reducing students' pre-identified misconceptions. To have well distributed questions, from simple to complex, we developed the pre/post quizzes based on Bloom's taxonomy. The *Taxonomy of Educational Objectives* developed by Bloom *et al.*[13] consist of six main categories in the cognitive domain of learning. The lowest three levels are: knowledge, comprehension, and application. The highest three levels are: analysis, synthesis, and evaluation. Inasmuch as Bloom's taxonomy is hierarchical in a context that each level is subsumed by a higher level, we aimed to include questions from each level of the taxonomy in our pre/post quizzes. To do so, we first came up with the pool of questions regarding Bernoulli's principle. Then, using mini-delphi model explained in section 2.1, the same panel of experts, with an addition of one professor from the College of Education, were invited to help and discuss the Bloom's level of each proposed question. Each member on the panel was provided with a copy of Bloom's taxonomy.

Moreover, considering the fact that the most meaningful assessment is provided when the same objective is compared among two different groups[14], that is for our purpose two different teaching styles, the same pre and post quizzes were utilized by a control group, a class of 48 students who just had lecture, and an experimental group, a class of 32 students who received a mini-orientation lecture and participated in a small three-person interactive hands-on learning session.

3. Results

3.1. Identifying Misconceptions – Bernoulli's Principle

A summary of the misconceptions identified by experienced professors on our panel is provided in Table 1. As shown in Table 1 and shown previously[15], one of the common misconceptions with students is that they cannot understand the relationship between pressure and velocity through the venturi and more importantly that energy must be conserved as the fluid flows through the venturi.

3.2. Ultra-Low-Cost Venturi Meter

Students tend to think pressure goes up at the throat of a venturi because fluid would squeeze to pass the small area. To reduce such conceptual difficulty and to help students to better understand the relationship between pressure and velocity through a contraction and expansion, we included vertical standpipes for measuring static heads at the inlet, throat and outlet of the venturi. In this case, students can see how pressure changes through the venturi and hopefully with the use of continuity they would know how velocity changes accordingly (Figure 2).

Table 1. Students' misconceptions regarding Bernoulli's principle from professors' prospective

Questions Professors	What are the misconceptions you have seen in students while teaching Bernoulli's principle?	Which misconceptions about Bernoulli's principle persist in students even after completing your class?
Prof. #1	Mainly there are misconceptions about compressibility and when it applies. Students often are thinking that the fluid is compressed when it goes through the throat. Also they don't really understand the Bernoulli model assumes no friction.	I think they get it after taking my class
Prof. #2	• The velocity is the dynamic term in the Bernoulli equation: flow speeds up as liquid travels downhill in a pipe, pipe friction causes liquid to slow down as it travels down a pipe, a pump receives energy and therefore velocity out is greater than velocity in; flow up-hill slows down. • Smooth pipes are frictionless so you can ignore h_{fs} • When looking at a real system, not realizing an energy balance is between two distinct points – students may use ΔP at the top of a reservoir and at a stream outlet, both of which are at 1 atm, KE (kinetic energy) somewhere within a pipe, heights somewhere else, or they may use a measured ΔP around a valve, fitting, pump, etc. and insert it as the ΔP for the whole system • Pressure increases as flow proceeds into a constriction, and decreases as it comes out. • Ignoring the fact that pressure is the dynamic term, rather than the kinetic energy.	• Students are apt to not understand how pressure and velocity changes in a venturi meter from point to point • Students have a difficult time digesting how energy changes for a packet of fluid going through the venturi • Students found use of the ME (mechanical energy) balance somehow difficult
Prof. #3	In the past, I gave students a venturi with a manometer attached to it and asked them to measure volumetric flow rate. Air pumped through the venturi and water was in manometer. Because students didn't understand what each term in the Bernoulli equation means, some of them: • used Δz measured between arms of the monometer for the venturi • used water density instead of air density in the Bernoulli equation • did not know the relationship between velocity and volumetric flow rate	I haven't done any experiments to see what misconceptions persist in students
Prof. #4	• Students believe that fluids slow down in a pipe. • Students have a hard time understanding Bernoulli's assumption of no viscous dissipation, which is conservation of mechanical energy • Students have hard times to apply Bernoulli in a real situation entails contradictory assumptions. Misunderstanding that even though we say viscous dissipation does not transform much mechanical energy into thermal energy, that there is still viscous dissipation in a pipe, and that pressure still drops a little (in comparison), although when pipe diameter decreases pressure drops a lot and when pipe diameter increases pressure rises.	I don't have any rigid data on this matter

3.3. Assessment of Learning

Open-ended questions provide students the opportunity to construct their own answer and allow instructors to discover unanticipated responses. However, as we have experienced open-ended questions can take considerable time for a student to construct a response.

Time constraints cause students not to get to all the questions, even with a short quiz. In cases where students answer question hastily but answer all the questions, even partially, may get higher rating than those who try to address all the details in their response and are not able to finish the entire exam.

On the other hand, the same number of close-ended multiple-choice questions can be answered in a shorter period of time. Moreover, in contrast to an open-ended questionnaire which takes significant time to be processed, the results of multiple-choice questionnaires take significantly less time for the researcher to analyze and digest. On the other hand, in contrast to open-ended questionnaires which let respondents freely develop their thoughts, multiple choice questionnaires limit the respondent to choose among a set of alternatives being offered by the researcher[16].

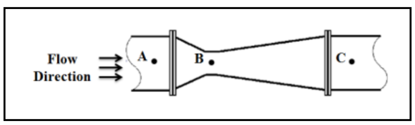
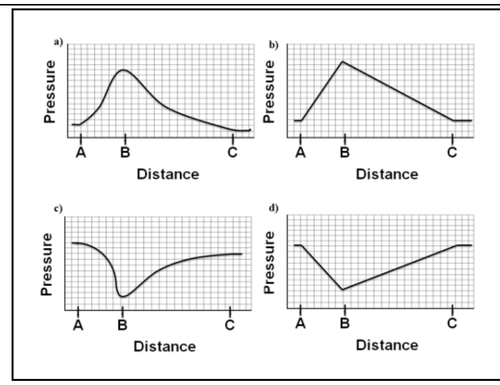
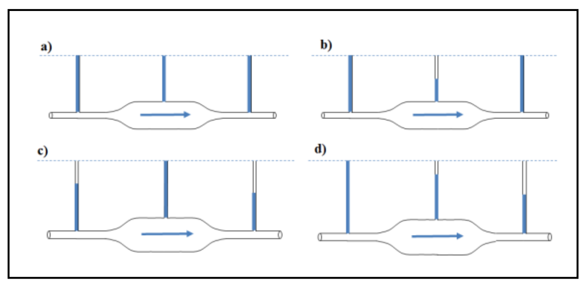
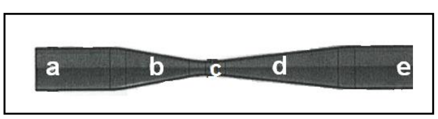
In developing our pre/post quizzes, we decided to derive benefits from both open-ended and multiple-choice questions. However, we chose to have more multiple-choice questions because:

1) Pre/post quizzes should not take more than 10 – 15 minutes of students' time during the 50 minutes class. It wouldn't be realistic to expect students to finish 7 – 10 open-ended questions in such a short time.
2) Open-ended questionnaires are especially recommended for surveys at initial stages or preliminary research so that appropriate answer categories can be identified[17]. However, from many years of experience teaching this particular course we have identified the typical misconceptions and can easily envelope those in multiple-choice questions.
3) As alluded to earlier, developing an answer key and rubric to assess student learning for open-ended questions is time consuming, whereas gaining results from multiple-choice questions takes less time.

While multiple-choice questions take less time for students to answer and researchers to assess, one should keep in mind that coming up with a set of qualified multiple-choice questions, on even a single topic, is not an easy task to accomplish. For each single question the given choices should have the same likelihood of selection if a misconception exists. When a well-designed question set is available, instructors will know which misconceptions exist or persist among students and can modify their course design to repair these misconceptions. After coming up with a pool of questions on Bernoulli's principle, assigning a Bloom's level to each question, and iterating final questions between authors several times to make sure all questions have clear objectives, we decided to test students' learning using the questions shown in Table 2.

Self-assessment types of questions stimulate students to express the certainty of their own knowledge[18]. As a result, after each question in pre/post quizzes, we asked students "How confident are you in your answer to the previous question?" and we gave them choices from "1 Not confident (I guessed)" to 5 "Confident (I know I am right)". Moreover, such questions help us as instructors to understand what students think and whether their answers are based on guesses, misconceptions or over-confidence, giving insight on how we should modify any step proposed in Figure 1 to better help students to apply their cognitive resources.

Table 2. Pre/Post Questions

Bloom's levels	Questions	Choices
Level 2 Comprehension	Bernoulli's equation says that along a streamline	a) Energy is conserved b) Mass is conserved c) Pressure is constant d) Pressure varies inversely with velocity
	Bernoulli's equation says that along a streamline	a) Velocity head is constant b) Pressure is constant c) Piezometric head is constant d) Total head is constant
Level 4 Analysis	Select the **<u>most realistic</u>** graph for pressure verses length for the venturi below. 	
	Circle the figure that most closely represents reality	
Level 3 & Level 6	Air flows from right to left in the figure. Which of the following statements is  correct?	a) pressure at (a) > pressure at (c) b) pressure at (a) < pressure at (c) c) pressure at (a) = pressure at (c)
		a) velocity at (a) > velocity at (c) b) velocity at (a) < velocity at (c) c) velocity at (a) = velocity at (c)
		a) mass flowrate at (a) > mass flowrate at (c) b) mass flowrate at (a) < mass flowrate at (c) c) mass flowrate at (a) = mass flowrate at (c)
	One of your classmates tells you your answers for 4-6 are wrong. Defend your reasoning.	Open-ended answer

3.3.1. Preliminary Results of Learning Assessments

For the purpose of this paper, and because one of the main misconceptions held by students regarding Bernoulli's principle (see Table 2) is that they cannot predict how pressure changes as a result of expansion or contraction, we present our assessment results for Bloom's level 4 questions in Table 2.

Students in the control group sat through a lecture while those in the experimental group were given a hands-on approach for learning about and applying Bernoulli's principles to a venturi meter. When appropriately covered in class an instructor would expect all students to understand the flow work transformation to kinetic energy as fluid passes through the throat of a venturi. However, as mentioned, this is both a common and persisting misconception among students and our aim is to assess how students' learning gains differ with different pedagogies regarding the venturi meter itself (third listed question in Table 2). Choices 'a' and 'b' were provided as possible answers because many students incorrectly think that as liquid squeezes through a smaller throat area pressure should go up. However, what makes choice 'b' different is that pressure at point C is equal to the pressure at point A. The reason behind putting this choice down is that some students think pressure may change if fluid goes through a contraction but it should come back to its initial pressure afterward. Choice 'd' was given because some students may understand that pressure should drop when velocity increases at point B; however, they think pressure should drop linearly and ignore the second order dependency of velocity on diameter, i.e., cross sectional area depends on the diameter squared. Furthermore, students may ignore the second order dependency of the flow work term on the velocity, i.e. the kinetic energy depends on the velocity squared for a net fourth order dependency on the diameter, which changes linearly with distance through the venturi meter. They also may believe that energy is fully recovered in the venturi meter, i.e., there are no frictional losses, and want to pick d because the pressure returns to the initial value.

As will be summarized in the following sets of tables, both lecture and hands-on pedagogies helped students in learning the Bernoulli's principle to an acceptable level. First, we note from Table 3 that there was large two-fold increase in the percent of students in the lecture cohort who properly understood the energy transitions after instruction. The higher numbers of students answering correctly came from all other categories, the largest fraction from those whose answers are consistent with the thought that flow through a constriction squeezes fluid causing higher pressures. In fact there was a 71% decrease in numbers of students who held to this incorrect notion. At the same time there was a 61% decrease in students who held to the idea that pressure increases, but that energy transitions are linearly related to diameter.

When looking at similar data for the hands-on group we see an increase in proper understanding; however a peculiarity exists from what has been observed in prior analyses of classroom data in that even in the pre-quiz a net 80% had the correct perception that pressure decreases in the throat with 63% seemingly having a correct understanding of the non-linear dependency of the pressure term on the tube diameter. There was a 15% drop in those who maintained a misconception of linear pressure variance with diameter and those seemed to have shifted their thinking to a proper understanding as the small net ~10% of students maintaining an incorrect understanding of flow work to kinetic energy transition remained the same after the post-quiz.

Table 3. Results from Pressure-Distance curve in a venturi meter

Groups	Quizzes	%students who chose a	%students who chose b	%students who chose c, right choice	%students who chose d
Lecture	Pre Quiz	29%	13%	38%	21%
	Post Quiz	8%	4%	79%	8%
Hands-on	Pre Quiz	3%	7%	63%	27%
	Post Quiz	3%	6%	68%	23%

To check if all students in both groups have understood how pressure relates to velocity and to maximize retention for hands-on students through the visual learning session they used venturi meters with static liquid head meters attached to indicate pressure as shown previously in Figure 2, we asked students how pressure changes if fluid flows from a smaller to larger cross-sectional area and then back to a smaller cross-sectional area tube (4^{th} question listed in Table 2). A summary of the results is provided in Table 4. There were similar improvements in proper conceptual understanding from 44 to 75% from the lecture group, and 50 to 71% students from the experimental hands-on group. The largest shift occurred in the percentage that improperly understood kinetic energy to the flow work transition.

Table 4. Pressure changes during flow through expansion and contraction

Groups	Quizzes	%students who chose a	%students who chose b	%students who chose c, right choice	%students who chose d
Lecture	Pre Quiz	4%	48%	44%	4%
	Post Quiz	4%	21%	75%	0%
Hands-on	Pre Quiz	10%	33%	50%	7%
	Post Quiz	3%	16%	71%	10%

In Table 5, we have reported our results for the combined set of questions at Bloom's level 4. When taken collectively we see similar improvements in conceptual understanding of the energy transition phenomena occurring when changing diameters with about 75% demonstrating a correct understanding whether flow proceeds from a larger to smaller or from a smaller to larger diameter. These combined results add strength to our argument that both the hands-on and lecture-based learning improve students' ability to correctly answer questions about the Bernoulli phenomena. What will be interesting is to add data from a second ongoing study in both mechanical and chemical engineering courses and to contrast student confidence about their understanding based on whether they had lecture or a mix of lecture and hands-on learning. We expect these results to be ready by the time of the ASEE conference and expect to report on those at that time.

Table 5. Percent of Students chosen right answer for both questions at Bloom's level 4

Quizzes	Lecture %students who answered correctly	Hands-on %students who answered correctly
Pre Quiz	41%	57%
Post Quiz	77%	74%

4. Conclusion:

Identifying misconceptions and developing strategies to abate or reduce such barriers are vital in guiding students' learning. Only by doing so, can we make sure that our graduates have obtained an appropriate level of knowledge, skill, and attitudes from the material taught in the class.

To determine students' misconceptions regarding Bernoulli's principle, we took advantage of the expertise of experienced faculty members who have taught the fluid mechanics course for years. With the goal of helping students with their identified conceptual difficulties and because we believe one's learning will be improved through visual presentation and active engagement with equipment that embodies engineering principles, we developed an ultra-low-cost, portable and low-weight venturi meter and implemented it in the classroom. Also, it is noteworthy to say that among the four professors on board only one had studied persistent misconceptions. More studies are needed to find out which misconceptions remain with students even after having either a lecture or hands-on session.

To check the efficacy of our pedagogy (hands-on active), we utilized pre/post quizzes and compared the results with the traditional pedagogy (lecture-based). Inasmuch as the hands-on experiment for this single topic is not repeatable for at least a semester and inasmuch as the results of such experiments greatly rely on how student outcomes in the pre/post quizzes differ in control and experimental groups, we certainly believe one should consider developing pre/post quizzes to be as important as any other step of a hands-on learning experimental design. We developed our pre/post quizzes based on Bloom's taxonomy levels so we could determine the learning level associated with each question, and we sought to have questions from each level of the taxonomy. We also considered the benefit from both open-ended and multiple choice questions in our quizzes but with focus on multiple-choice questions because they create data that is easily quantifiable. However, for future studies, we will consider having more choices for any single question so that we could make sure that all misconceptions on any question are covered.

Based on our results, by substituting lecture with hands-on, students seem to learn as well as lecture; however, students in the hands-on groups get to experience a real-world engineering system and learn how to work in a team. Further analysis of the results to include other study groups and confidence in answer information will be presented at ASEE.

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