

Prevalence and consistency of student ideas on simple dc circuits: A comparison between high school and undergraduate students

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This study compares conceptual understanding, as well as the prevalence and consistency of student ideas regarding simple dc circuits, between two distinct groups: high school students after initial instruction ($N = 1274$) and undergraduate students in physics-related degree programs before attending university lectures ($N = 423$). To investigate student ideas, we employed the 2T-SEC test, a two-tier multiple-choice instrument. Results show a significantly higher conceptual understanding among undergraduates (Cohen's $d = 0.96$). However, the overall prevalence of specific student ideas appears to be similar across both groups: of the 13 student ideas examined, 5 occur equally often, 4 are more frequent among high school students, and 4 among undergraduates. Notably, certain ideas well documented in the literature, such as “sequential reasoning” and “current consumption,” are significantly more prevalent among undergraduates. Consistency analyses reveal generally low levels across both groups, with few significant group differences. Moreover, these findings suggest that everyday experiences and language may reinforce certain student ideas over time.

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I. INTRODUCTION

Electricity plays a central role in modern society, powering everything from basic lighting to electric vehicles. As a result, understanding simple direct current (dc) circuits has become a core component of secondary school curricula internationally. In Austria and Germany, this topic is typically introduced in grades 7 or 8 and taught over the course of 18–20 teaching units at the time of the present

study [1]. Despite its curricular prominence, research consistently shows that students encounter substantial difficulties in developing a coherent understanding of basic circuit concepts such as current, voltage, and resistance. One major challenge lies in the abstract nature of these quantities and their lack of direct sensory accessibility [2]. Everyday experiences with electricity, such as flipping switches or changing batteries, rarely support scientifically accurate mental models. Instead, learners often develop intuitive yet frequently nonscientific ideas about electric circuits that may persist even after formal instruction.

A large body of physics education research has documented typical student ideas in the domain of simple dc circuits at both secondary and university levels [2–4]. These studies demonstrate not only that such ideas are widespread but also that some of them appear remarkably resistant to instructional change. However, most existing research has examined student ideas within isolated educational stages or specific instructional interventions [2,5,6]. As a result, systematic evidence on how student ideas evolve or persist across educational trajectories remains limited.

In this study, which forms part of a joint research project involving Physics Education Research Groups in Germany

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and Austria, we address this gap through a cross-population comparative design employing the 2T-SEC test [7], a validated two-tier multiple-choice instrument. Using the same test, we compare two distinct learner populations: (i) high school students immediately following their first formal instruction on simple dc circuits, and (ii) undergraduate students enrolled in physics-related degree programs prior to any university-level coursework. These groups represent highly heterogeneous populations. High school students in this study constitute a broad learner cohort that was taught about simple electric circuits shortly before data collection. Undergraduate physics students, in contrast, represent a positively self-selected group; as a result, they can be expected to exhibit higher disciplinary interest, more advanced formal reasoning skills, and a better conceptual understanding of electric circuits. This contrast allows us to examine which student ideas persist even under conditions of strong self-selection and increased academic commitment. Such persistent ideas are particularly relevant for university teaching, where instruction often implicitly assumes a substantial alignment of students' prior conceptions with scientific models, and where students' ideas are therefore less frequently addressed explicitly [8].

Moreover, because simple dc circuits in Germany and Austria are usually addressed only in lower secondary education, both groups have received comparable formal instruction on this content. Observed differences may therefore offer exploratory insights into the effects of everyday experiences with electricity, which may contribute to the long-term reinforcement of certain student ideas.

II. THEORETICAL BACKGROUND

A. Student ideas on simple dc circuits

Research has shown that students do not come to class as *tabula rasa* but instead develop intuitive ideas about physical phenomena based on everyday experiences and linguistic expressions (e.g., “empty batteries”) even before receiving formal instruction [9]. Physics education research has long investigated such ideas, which often differ from accepted scientific explanations. Over time, various theoretical perspectives have been proposed to describe their structure and origins, ranging from coherent theorylike conceptions to context-dependent knowledge elements [10–13]. This diversity has also led to a wide range of terminologies, such as “misconceptions,” “alternative frameworks,” “naïve concepts,” “phenomenological primitives” or “p-prims,” “children’s science,” “preconceptions,” and “alternative conceptions” [14,15]. Although frequently used, the term “misconception” has been widely criticized for its negative connotations [16] and its failure to recognize the ecological validity of many student ideas in everyday life [17]. Against this backdrop, we use the term “student ideas” to refer to student answers and explanations that are inconsistent with the scientific view, following Refs. [18,19].

Building on a substantial body of physics education research, we draw on several decades of work documenting common student ideas about simple dc circuits across many instructional contexts and age groups. One particularly well-documented example is the student idea that electric current is used up as it flows through a circuit [15,16]. International studies show that this student idea is not only held by young students before instruction [14,20] but also remains widespread in lower secondary education. For example, Licht and Thijs found that 61% of 13- to 14-year-old students expressed current consumption reasoning [5]. Similar reasoning has also been reported among older secondary students after instruction [2] and even among university students in technical majors [21]. Such findings suggest that at least some student ideas may persist across educational stages.

Beyond current consumption, the literature reports several further student ideas in the domain of simple dc circuits. These include beliefs that current gradually attenuates in series circuits [22] and that batteries act as constant sources of current independent of circuit resistance [3–6,23,24]. Studies at both secondary and university levels indicate that sequential reasoning and battery-as-current-source conceptions can remain prevalent even beyond school instruction [3,4]. A particularly persistent form of reasoning is sequential reasoning, which refers to the view that current flows stepwise from one battery terminal through each circuit element in turn [25–27]. This idea has been documented among secondary school learners [2,23] and is also frequently observed among university students, suggesting substantial persistence across educational stages [3,4].

Additional challenges concern the concept of voltage. Many students conflate voltage and current and assume that potential difference can only occur when current flows, resulting in the belief that no voltage exists across an open switch [2,23,28]. Importantly, voltage-related misconceptions appear particularly robust: such reasoning is reported not only among secondary school students but also among undergraduates, indicating strong persistence beyond school instruction [3,4].

Beyond these, further student ideas are described in the literature, including difficulties in recognizing closed electric circuits [14], the belief that increasing resistance leads to an increase in current [15], the necessity of closed circuits for bulbs to light [3], and student ideas about the effects of combining batteries in a circuit [16].

Overall, the literature describes a broad range of student ideas in the domain of simple dc circuits. Most studies have been conducted with populations from secondary education, where such conceptions are consistently found to be widespread. Only a smaller number of investigations explicitly include university-level learners; yet these studies indicate that certain ideas (such as current consumption, sequential reasoning, or difficulties with voltage in open circuits) can be remarkably robust even among undergraduate students who

have chosen scientific or engineering fields. However, the existing evidence largely stems from separate studies employing different instruments and research designs. As a consequence, there is still a lack of systematic research that compares the prevalence and persistence of specific student ideas across educational stages using comparable measurement approaches.

B. Theoretical perspectives on the structure of student ideas

Research has shown that student ideas are highly resistant to change [29–32], meaning they often persist even after instruction in upper-level university courses [32]. This is attributed to the fact that, despite their limited generalizability, these student ideas often have a seemingly high ecological validity in students' everyday life [17]. At the same time, student ideas have proven to be highly flexible cognitive constructs with a high degree of contextuality [33,34]. This means that a physically identical situation can—depending on the context—activate different student ideas. The duality of stability and flexibility has led to an ongoing debate about the epistemological nature of students' ideas about the physical world [11,18,35].

Building on the observation that students around the world show similar and persistent student ideas, the knowledge-as-theory perspective suggests that these ideas are the result of a small set of coherent and stable mental structures [11,36]. These structures develop as children unconsciously integrate diverse everyday experiences into a relatively coherent knowledge structure, forming a coherent explanatory framework with theorylike properties (“framework theory”) that strongly shapes how students perceive, interpret, and explain the physical world [11]. Early proponents of this perspective even suggested that the resulting theorylike cognitive structures of students had a degree of coherence similar to physical theories in the history of science, e.g., the impetus theory [10]. This, however, is disputed by Vosniadou and Skopeliti, who argue that students' framework theories differ from scientific theories in that they do not exhibit the same degree of internal consistency and explanatory power [11]. In their interpretation, inconsistencies in student ideas do not necessarily reflect fragmented knowledge. Rather, the framework theory provides a very general structure of ontological categories within which contextual variation is possible. What appears as fragmented knowledge is, from the knowledge-as-theory perspective, the blending of a coherent framework theory with additional context-specific experiences.

A fundamentally different view of the epistemological nature of student ideas was proposed by diSessa with his knowledge-in-pieces perspective [13]. According to this framework, students' understanding of physics is not theorylike but rather composed of a loosely connected collection of small, context-sensitive knowledge elements

known as p-prims (phenomenological primitives) [37]. These p-prims represent intuitive knowledge fragments that are minimally abstracted from everyday experiences in the physical world and typically have limited explanatory power, such as the p-prim “more cause yields more effect” [38], which can manifest in electric circuits as the expectation that adding a battery necessarily increases the current everywhere in the circuit. As diSessa puts it, p-prims may be “as atomic and isolated a mental structure as one can find” [38].

Within this perspective, students' understanding of the physical world is assumed to be fragmentary rather than coherent, as everyday life does not require a unified theory of the physical world. diSessa emphasizes that students do not enter physics instruction with a stable theory, but rather approach problems on a “catch-as-catch-can” basis, applying different naïve logics depending on the context [13]. Scientific concepts, in this view, develop through the refinement and appropriate coordination of p-prims into more structured knowledge systems known as coordination classes [39], while student ideas emerge from the inappropriate activation or uncoordinated use of p-prims.

More recently, the knowledge-in-pieces framework has been extended and generalized in what is often referred to as the resources perspective [40,41]. As introduced by Hammer [42,43], this view conceptualizes student ideas as cognitive resources, that is, flexible knowledge elements that can be activated individually or in combination, depending on the context. These resources include p-prims, as well as broader conceptual and epistemological resources. This flexible and dynamic use of cognitive elements supports the idea that students' reasoning is not necessarily flawed but rather shaped by the structure and availability of resources in a given moment [42]. Consequently, in the knowledge-in-pieces or resource-based view, consistency arises when the same contextual features repeatedly cue the same set of intuitive resources, often p-prims, leading to similar responses even years later. At the same time, small changes in context may activate a different subset of resources, producing seemingly inconsistent reasoning patterns across superficially similar tasks.

III. RESEARCH QUESTIONS

Although student ideas in the domain of simple dc circuits are well documented in the literature, less is known about how their prevalence and consistency vary across educational groups. In particular, empirical evidence on the consistency with which such ideas are applied across contexts remains limited, especially for simple electric circuits. Building on a contrastive comparison between two educational groups differing in age and self-selection into physics-related studies (high school students after instruction and undergraduate students in physics-related degree programs prior to their first university physics

course on the topic), we address the following research questions:

1. How does the prevalence of student ideas on simple dc circuits differ between high school students after instruction and undergraduate physics students prior to university-level instruction?
2. How consistent are student ideas about simple dc circuits among high school students after instruction and undergraduate students prior to university-level instruction across different isomorphic items?

IV. METHODS

A. Test instrument

Over the past decades, numerous research projects in physics education have investigated and categorized student ideas using qualitative and quantitative methods, leading to a wealth of knowledge, particularly in the field of electricity [44]. Based on this knowledge and our own research, we developed a Rasch-scaled two-tier multiple-choice test instrument (the 2T-SEC test), originally developed in German and later published in English, which is suitable for reliably assessing the conceptual understanding of simple dc circuits in high school and undergraduate students [7]. The use of two-tier items, requiring students to provide an explanation to their answers, can represent an effective way of assessing meaningful learning, as it addresses some of the limitations of traditional multiple-choice tests [45]. Two-tier tests, however, have been criticized for the fact that students’ responses may result from a lack of knowledge rather than a firmly held student

idea [46]. Nonetheless, such instruments have been found to be successful in science education research [47,48].

Our test instrument consists of 25 two-tier items focusing on basic concepts of simple dc circuits, such as current, voltage (potential difference), and resistance, which students generally learn about in all schools in grades 7 and 8 in Germany and Austria. Each of the 25 items consists of two subquestions (tiers), with the first tier requiring students to answer a content question and the second tier asking them for an explanation for their answer in the first tier. The advantage of such a two-tier multiple-choice test is that it provides deeper insights into students’ thinking about electrical circuits, eliminates false positives (i.e., correct answers with inadequate explanations), and is easy to administer to large groups of students. Since the distractors of the test instrument are based on research findings on students’ difficulties with electric circuits, the two-tier structure allows for the identification of several typical student ideas. Figure 1 shows a sample item of the test instrument that illustrates how typical student ideas can be identified using its two-tier structure.

Students who state that “The current at point A is larger than at point B” or “The current is larger at point B than at point A” in the first tier and “The current is consumed by the light bulb” in the second tier are interpreted to hold the student’s idea that “Current is used up.” Eight experts from the PER groups of the Austrian-German collaboration assigned specific combinations of answers from the first and second tiers to student ideas for all 25 items of the test instrument. This was done through a consensus-based procedure. An overview of which student ideas were

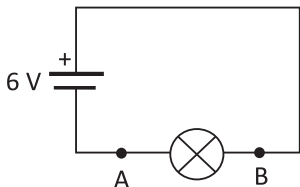
Item 9		The circuit shown below consists of a battery and a light bulb. The light bulb is shining.	
(a)		What can you say about the current at points A and B?	
A	☐	The current at point A is larger than at point B.	
B	☐	The current is larger at point B than at point A.	
C	☐	The current is the same at point A and B.	
(b)		Why? Choose the statement that best fits your reasoning.	
A	☐	The current is consumed by the light bulb.	
B	☐	The current is the same at every point in the circuit.	
C	☐	The current decreases as the distance to the battery increases.	

FIG. 1. Sample item on electric current from the 2T-SEC test.

TABLE I. Overview of the student ideas assessed in the study using the 2T-SEC test, with a brief description as well as the items, answer combinations, and the number of items they were assessed with.

	Student idea	No. of items	Description	Items and answer combination
1A	There is no voltage in an open circuit	1	Students believe that there is no potential difference between the ends of two wires, each connected to a different terminal of a battery.	12 AB, AD
1B	Sequential reasoning	1	Students believe that the direction of current and the sequence of circuit elements are important as they examine the circuit from the perspective of charge flowing sequentially through the circuit, e.g., starting at one terminal of the battery.	24 AA, BA
1C	When batteries are connected in parallel, the voltage increases	1	Students believe that when batteries are connected in parallel, the total voltage is the sum of the voltages of the individual batteries.	19 BB
1D	In parallel circuits, the current is the same in all branches (overgeneralization of $I = \text{const}$)	1	Students believe that the current is the same in all the branches of a parallel circuit (a conception that might be due to an overgeneralization of the rule $I = \text{const}$ for unbranched circuits).	15 AA
1E	A current only occurs when the applied voltage matches the light bulb's nominal voltage	1	Students believe that a light bulb only lights when the voltage of a battery matches the voltage for which the light bulb is built.	3 BA
2F	Difficulties in recognizing that bulbs only light up in closed circuits	2	Students believe that a light bulb will light in an open circuit, or if it is connected in series with a broken bulb, or if only connected to one terminal of a battery.	1 AB, BA 11 AC, CB, DA
2G	The voltage is shared between resistors connected in parallel	2	Students believe that the voltage of the battery is evenly divided between resistors connected in parallel.	7 DB 8 AC
2H	Voltage is used up	2	Students believe that resistors and light bulbs consume the voltage.	14 AC, BC 17 BA
2I	The load determines the applied voltage	2	Students believe that a light bulb always operates at its rated voltage, independent of the power source.	3 DC 19 CA
3J	Lack of differentiation between voltage and current	3	Students believe that the voltage between any points in a simple circuit is the same because the current is the same throughout the entire circuit.	12 AB, AD 14 CA, DA 17 AE, CE, DE
3K	Battery as a constant source of current	3	Students believe that the current in an electric circuit is determined by the battery, not by the total resistance of the circuit.	4 CA 5 CA 16 BF
3L	Current is used up	3	Students believe that current is consumed (in part) by light bulbs.	9 AA, BA 15 BC 18 AA, CA, DB
3M	Inverse concept of electric resistance	3	Students believe that the greater the (total) resistance, the greater the current intensity.	4 AD 5 AE, BC 16 AB, CC

TABLE II. Overview of the sample of the study.

	High school students		Undergraduate students
	Group A	Group B	
<i>N</i>	629	645	423
Gender	$m = 341, f = 284, d = 4$	$m = 336, f = 304, d = 5$	$m = 226, f = 192, d = 5$
Country	Austria: 348 Germany: 281	Austria: 358 Germany: 287	Austria: 28 Germany: 395
Grade/semester	7th grade		$M = 2.10$ semester (SD = 1.39)
Field of study	Physics in high school		Physics (major): 139 Physics (minor): 195 Physics (teaching degree): 89
Prior experience	Unit on simple dc circuits		No prior experience at university: 390 Undergraduate lab course: 33

surveyed with which combinations of answer (first tier) and explanation (second tier) in the 2T-SEC test is shown in Table I as well as a brief description of the respective student ideas. As can be seen from the table, the different student ideas were each assessed with one, two, or three items.

It should be noted that the instrument was not originally designed to support direct comparisons of the prevalence of different student ideas. Individual student ideas are operationalized using differing numbers of items and, within items, differing numbers of coded response combinations. Consequently, direct between-idea comparisons (e.g., assessing whether sequential reasoning is more prevalent than current consumption) are methodologically unwarranted. Accordingly, the present analysis is restricted to within-idea comparisons, examining whether a given student idea (e.g., sequential reasoning) occurs with different frequencies across learner groups.

B. Data collection

As part of the joint research project, the Physics Education Research Groups of Germany and Austria administered the 2T-SEC test to high school students and undergraduate students. All data collection took place during regular instructional time. For the high school group, the test was administered at the end of the instructional unit on simple dc circuits, whereas for the undergraduate group, it was administered during the first lectures of the first semester.

Undergraduate students completed the full version of the instrument, comprising all 25 two-tier items. In contrast, the high school sample was randomly divided within each class into two subgroups (group A and group B), each of which completed only a subset of the test items: All high school students answered items 1–11. In addition, group A completed items 12–19, whereas group B responded to items 20–25. This anchor-test design with a shared set of

core items (items 1–11) was used to reduce cognitive load and time pressure for the younger participants.

C. Sample

Two groups of seventh-grade high school students (aged approximately 12–13 years) took part in the study immediately after completing instruction on simple dc circuits: Group A ($N = 629$) and group B ($N = 645$). This division reflects the split-test design described above. In addition, $N = 423$ undergraduate students enrolled in physics-related degree programs were assessed prior to any university-level instruction on electric circuits, including 33% physics majors (enrolled in a B.Sc. degree program), 46% physics minors (enrolled in a B.Sc. program in the natural sciences), and 21% preservice physics teachers (enrolled in a B.Ed. degree program). An overview of the sample composition is provided in Table II.

D. Data analysis

The student ideas analyzed in this paper were assessed using the 16 items listed in Table I. To ensure comparable sample sizes across items within the high school group, analyses were restricted to responses from group A. The only exception was item 24, which assesses sequential reasoning and was administered exclusively to group B.

The data analysis proceeded in three consecutive steps, addressing conceptual understanding, the prevalence of student ideas, and their consistency across isomorphic items.

First, students' conceptual understanding of simple dc circuits was analyzed using Rasch modeling. Rasch analyses were conducted using the TAM package in R [49]. Person abilities were estimated using weighted likelihood estimation, and item difficulties were jointly calibrated for high school and undergraduate students on a common latent scale.

Second, the prevalence of student ideas was examined based on the consensus-based expert classification described above. For each student's idea, responses were coded dichotomously (expressed vs not expressed). For student ideas assessed with more than one item, an idea was coded as expressed if it occurred in at least one item. Note that this operationalization reflects a context-sensitive view of student reasoning and is not intended to imply that student ideas are stable or internally coherent entities. Rather, it captures whether a given way of reasoning can be elicited in at least one context; consistency across contexts was analyzed separately.

Prevalence rates were calculated separately for high school and undergraduate students, considering only participants who had completed all relevant items. Group differences in prevalence were tested using Pearson's χ^2 tests. To account for multiple comparisons across student ideas, p values were adjusted using the Benjamini-Hochberg (BH) procedure. Statistical significance was determined based on BH-adjusted p values, with a significance threshold of $p_{\text{adj}} \leq 0.05$, corresponding to a false discovery rate (FDR) of $q = 0.05$. The BH correction was applied separately within each set of analyses. Note that all group comparisons are restricted to within-student ideas. Between-idea comparisons were therefore deliberately avoided as individual student ideas are operationalized using differing numbers of items and, within items, differing numbers of coded response combinations. Consequently, direct between-idea comparisons (e.g., assessing whether sequential reasoning is more prevalent than current consumption) are methodologically unwarranted.

Third, the consistency of student ideas was analyzed for those ideas assessed with two or three items. Consistency was operationalized as repeated expression of the same student idea across multiple items. For ideas assessed with two items, consistency was defined as the expression of the idea in both items. For ideas assessed with three items, two levels of consistency were distinguished: expression in at least two items and expression in all three items. Group differences in consistency were again examined using Pearson's χ^2 tests with BH correction.

V. RESULTS

A. General test results

Before presenting the main findings of the study, we report the results of the Rasch analysis of the response data obtained with the test instrument. The model demonstrated satisfactory item fit and a person separation reliability coefficient of 0.76 (see Supplemental Material [50] for detailed model fit statistics).

Person ability estimates served as the basis for group comparisons. As shown in Table III, undergraduate students exhibited higher average person abilities than high school students. The difference was statistically significant

TABLE III. Descriptive statistics of Rasch person ability estimates by group.

	Person ability (logits)		
	Mean	SD	SE
High school	-0.28	1.08	0.03
Undergraduate	0.87	1.51	0.07

[$t(568.46) = -14.374, p < 0.001$] with a large effect size (Cohen's $d = 0.96$), indicating that undergraduate students show a higher conceptual understanding of simple dc circuits.

B. Prevalence of student ideas of high school and undergraduate students

To compare both groups regarding the prevalence of specific student ideas, we conducted chi-square tests on the relative frequencies of each student idea, applying the Benjamini-Hochberg procedure to correct for multiple testing. For student ideas assessed with more than one item, the idea was considered present if students responded in accordance with the idea on at least one of the two (or of the three) items. Percentages were calculated based only on students who had completed all associated items on both tiers. As shown in Figs. 2 and 3, all student ideas occur with frequencies ranging from 7% to 81%. As noted earlier, frequencies cannot be meaningfully compared across different ideas; therefore, and in line with the research question, the following analyses focus exclusively on within-idea group comparisons. Student ideas showing statistically significant differences between groups are illustrated in Fig. 2, revealing a mixed pattern: four are more prevalent among high school students and four among undergraduates. The idea "current is the same in all parallel branches" (difference of 15.7 percentage points), "inverse concept of electric resistance" (15.4), "no voltage in open circuit" (10.8), and "battery as a constant current source" (10.2) occur significantly more often among high school students (all $p < 0.01$ or $p < 0.001$). In contrast, the idea "sequential reasoning" (difference of 20.6 percentage points), "current is used up" (14.7), "current only if voltage matches bulb" (10.8), and "voltage is used up" (7.0) are significantly more prevalent among undergraduate students (all $p < 0.01$ or $p < 0.001$). Furthermore, student ideas without significant group differences are shown in Fig. 3: "parallel batteries increase the voltage," "difficulties in recognizing that bulbs only light up in closed circuits," "voltage is shared across parallel resistors," "load determines applied voltage," and "voltage-current confusion." It is particularly striking that undergraduate students hold 4 of the 13 student ideas more frequently and 5 at comparable levels as high school students, despite having chosen to pursue a physics-related degree. Of particular note is the finding that the student

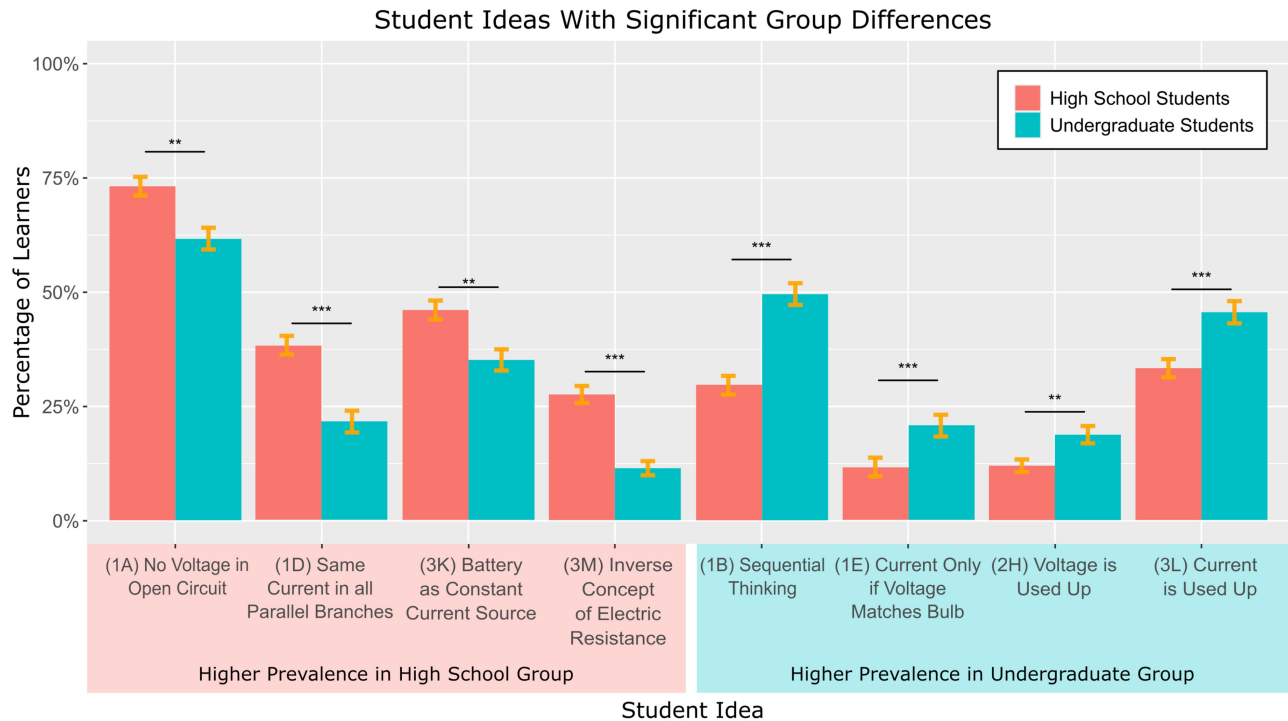


FIG. 2. Student ideas with significant group differences. Percentage of high school and undergraduate students who were assigned a given idea assessed with one, two, or three items. The error bars represent the standard error. Group differences were tested using Pearson's χ^2 tests; p values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure. Levels of significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$). Note that frequencies cannot be meaningfully compared across items; only group differences within individual items can be interpreted.

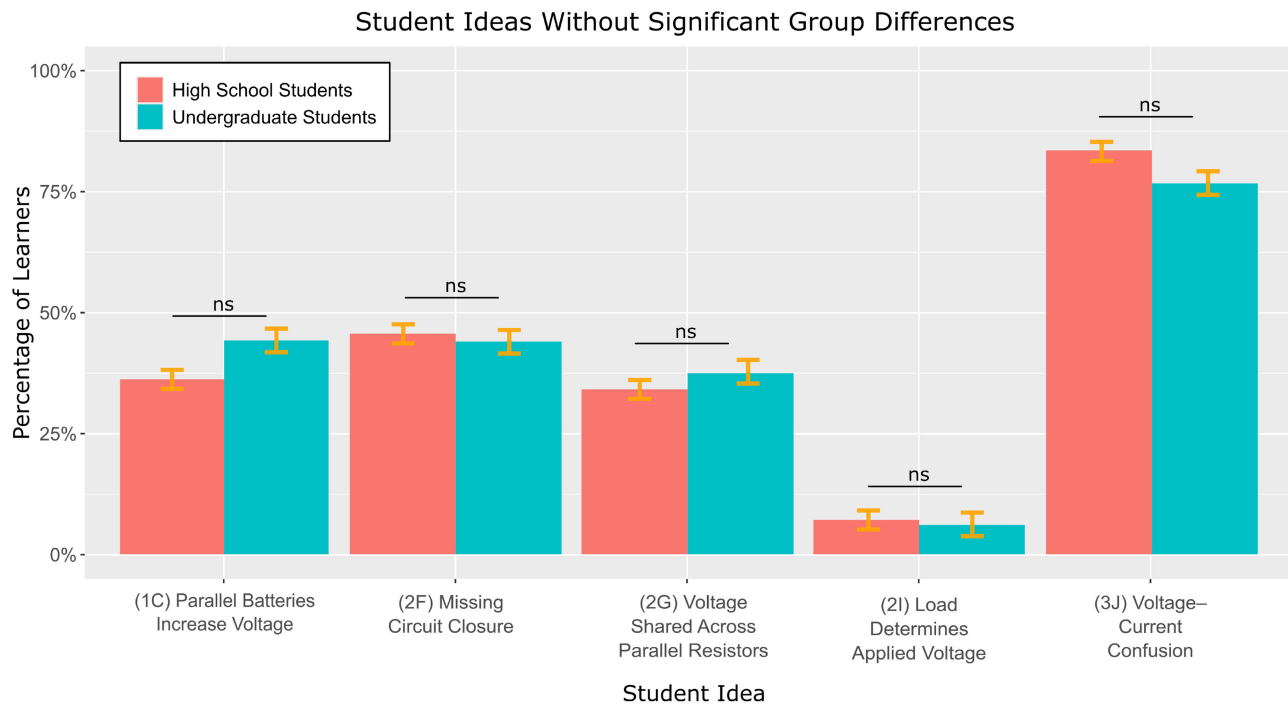


FIG. 3. Student ideas without significant group differences. Percentage of high school and undergraduate students who were assigned a given idea assessed with one, two, or three items. The error bars represent the standard error. Group differences were tested using Pearson's χ^2 tests; p values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure. Note that frequencies cannot be meaningfully compared across items; only group differences within individual items can be interpreted.

ideas “sequential reasoning” and “current is used up,” both widely documented in the literature, are significantly more common among undergraduates. An overview of the mean values obtained and the results of the chi-square test can be found in Table IV.

C. Consistency of high school and undergraduate student ideas

To investigate the consistency with which students express their ideas, we examined how many of the students who responded according to a particular student idea in one item also did so in at least a second (or even a third) item. In this context, it is important to keep in mind that four student

ideas were assessed with two items each (shown on the left in Fig. 4) and four student ideas were assessed with three items each (shown on the right in Fig. 4). For student ideas assessed with three items, a distinction is made between cases in which the idea is expressed in at least two items (indicated by bar charts) and those in which it is expressed consistently across all three (indicated by dashed lines).

The relatively low overall consistency becomes especially evident when examining whether the student’s ideas are expressed across all three items. Only the student ideas “lack of differentiation between voltage and current”—with proportions of 8.2% (high school students) and 7.4% (undergraduate students)—and “current is used up” among

TABLE IV. Overview of the percentage of high school and undergraduate students holding student ideas assessed with one, two, or three items, as well as the results of the chi-square test. A student was considered to have expressed a student idea if they responded in accordance with it in at least one of the corresponding items. p values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure.

	Student idea	High school students	Undergraduate students	Chi-squared statistics
		M [%] (SE)	M [%] (SE)	
1A	There is no voltage in an open circuit	73.5 (1.8)	62.7 (2.7)	$\chi^2(1) = 11.16$, $p = 0.002$ $\phi = 0.11$, $n = 941$
1B	Sequential reasoning	29.2 (1.8)	49.8 (2.8)	$\chi^2(1) = 38.70$, $p < 0.001$ $\phi = 0.21$, $n = 938$
1C	When batteries are connected in parallel, the voltage increases	36.2 (2.0)	42.9 (2.8)	$\chi^2(1) = 3.63$, $p = 0.082$ $\phi = 0.07$, $n = 915$
1D	In parallel circuits, the current is the same in all branches (overgeneralization of $I = \text{const}$)	39.3 (2.0)	23.6 (2.4)	$\chi^2(1) = 22.39$, $p < 0.001$ $\phi = 0.16$, $n = 917$
1E	A current only occurs when the applied voltage matches the light bulb’s nominal voltage	12.2 (1.3)	23.0 (2.3)	$\chi^2(1) = 17.49$, $p < 0.001$ $\phi = 0.14$, $n = 929$
2F	Difficulties in recognizing that bulbs only light up in closed circuits	40.9 (2.0)	44.1 (2.8)	$\chi^2(1) = 0.73$, $p = 0.427$ $\phi = 0.03$, $n = 901$
2G	The voltage is shared between resistors connected in parallel	34.6 (2.0)	37.9 (2.8)	$\chi^2(1) = 0.81$, $p = 0.427$ $\phi = 0.03$, $n = 885$
2H	Voltage is used up	11.9 (1.1)	18.9 (1.5)	$\chi^2(1) = 7.62$, $p = 0.009$ $\phi = 0.10$, $n = 877$
2I	The load determines applied voltage	7.9 (1.1)	7.3 (1.5)	$\chi^2(1) = 0.04$, $p = 0.842$ $\phi = 0.01$, $n = 896$
3J	Lack of differentiation between voltage and current	80.8 (1.7)	76.4 (2.4)	$\chi^2(1) = 2.13$, $p = 0.189$ $\phi = 0.05$, $n = 869$
3K	Battery as a constant source of current	45.9 (2.1)	35.7 (2.7)	$\chi^2(1) = 8.39$, $p = 0.007$ $\phi = 0.10$, $n = 897$
3L	Current is used up	33.2 (0.2)	47.9 (2.8)	$\chi^2(1) = 18.01$, $p < 0.001$ $\phi = 0.15$, $n = 883$
3M	Inverse concept of electric resistance	27.5 (1.9)	12.1 (1.8)	$\chi^2(1) = 25.55$, $p < 0.001$ $\phi = 0.18$, $n = 897$

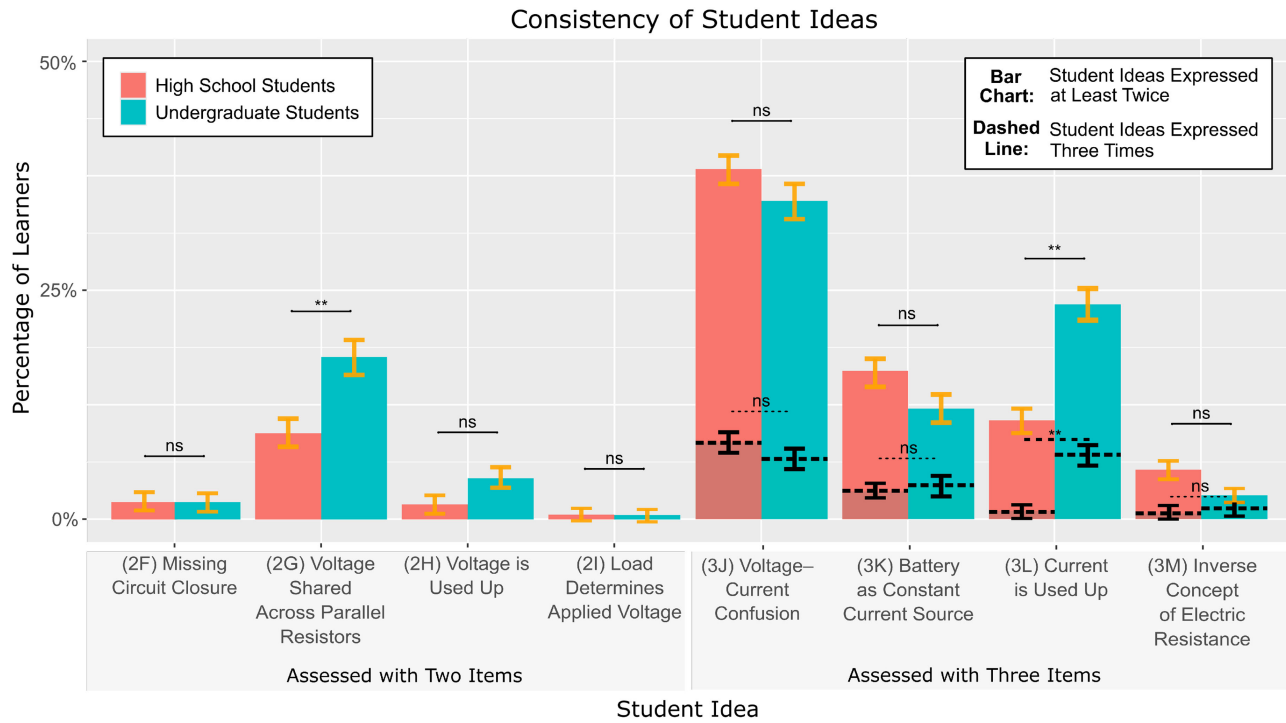


FIG. 4. Percentage of high school and undergraduate students who answered according to a particular student idea in one item and did so again in at least one more item. Only students who completed all items associated with the respective student idea were considered. Student ideas on the left were assessed with two items, and on the right with three items. For the items on the right, a distinction is made based on the frequency with which a student's idea is expressed: student ideas appearing in at least two items are marked with colored bar charts; those expressed in all three items are additionally indicated by a dashed line. The error bars represent the standard error. Group differences were tested using Pearson's χ^2 tests; p values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure. Levels of significance: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

TABLE V. Percentage of high school and undergraduate students who demonstrated a given student idea in at least two items, along with results of the chi-square test. The four student ideas in the upper half of the table were assessed with three items and four in the lower half with two items. p values were adjusted for multiple comparisons using the Benjamini-Hochberg procedure.

Student idea		High school students	Undergraduate students	Chi-squared statistics
		M [%] (SE)	M [%] (SE)	
2F	Difficulties in recognizing that bulbs only light up in closed circuits	1.9 (0.6)	2.8 (0.8)	$\chi^2(1) < 0.01$, $p = 1$ $\phi = 0.01$, $n = 901$
2G	The voltage is shared between resistors connected in parallel	9.4 (1.2)	17.4 (2.1)	$\chi^2(1) = 11.34$, $p = 0.005$ $\phi = 0.12$, $n = 885$
2H	Voltage is used up	1.6 (0.5)	3.7 (1.1)	$\chi^2(1) = 3.02$, $p = 0.137$ $\phi = 0.07$, $n = 877$
2I	The load determines applied voltage	0.5 (0.3)	0.6 (0.4)	$\chi^2(1) = 0.00$, $p = 1$ $\phi = 0.01$, $n = 896$
3J	Lack of differentiation between voltage and current	38.2 (2.1)	35.7 (2.7)	$\chi^2(1) = 0.44$, $p = 0.726$ $\phi = 0.02$, $n = 869$
3K	Battery as a constant source of current	16.2 (1.5)	10.9 (1.7)	$\chi^2(1) = 4.32$, $p = 0.095$ $\phi = 0.07$, $n = 897$
3L	Current is used up	10.8 (1.3)	23.7 (2.4)	$\chi^2(1) = 24.90$, $p = 0.005$ $\phi = 0.12$, $n = 885$
3M	Inverse concept of electric resistance	5.4 (0.9)	2.5 (0.9)	$\chi^2(1) = 3.52$, $p = 0.12$ $\phi = 0.07$, $n = 897$

undergraduate students (7.3%) show notable levels of (low) consistency.

Moreover, no substantial group differences are observed with respect to consistency. Among the eight student ideas analyzed in this section, significant differences are observed in only three cases. Undergraduate students respond significantly more consistently for two student ideas: “voltage is shared between resistors connected in parallel” (difference of 8.2 percentage points, $p = 0.005$) and “current is used up” (difference of 12.9 percentage points, $p = 0.005$). The idea “current is used up” is the only one for which a significant group difference remains when full consistency across all three items is required, with undergraduate students displaying a higher rate of consistent responses (difference of 6.2 percentage points, $p = 0.002$). An overview of the mean values obtained and the results of the chi-square test can be found in Table V.

VI. DISCUSSION

A. Discussion of research findings

Research question 1: How does the prevalence of student ideas on simple dc circuits differ between high school students after instruction and undergraduate physics students prior to university-level instruction?

In this study, we examined conceptual understanding as well as the prevalence and consistency of student ideas in two distinct groups: a group of high school students after initial instruction on simple dc circuits, and a group of undergraduate students enrolled in physics-related degree programs prior to their first university-level lectures. Overall, student ideas occur with roughly similar frequencies in both groups, although specific differences can be observed. At the same time, undergraduate students exhibit a significantly better conceptual understanding, corresponding to a large effect size (Cohen’s $d = 0.96$). This may seem contradictory at first glance, but it suggests that, on average, the proportion of response combinations in the two-tier items that are neither scientifically correct nor attributable to any identified student idea is higher among high school students. Thus, a central finding of this study is that, at the group level, a higher conceptual understanding in one group does not necessarily coincide with a reduced prevalence of student ideas.

Taken together, the results do not indicate a systematic group difference in the prevalence of student ideas. Rather, the pattern is mixed, with some ideas occurring more frequently among high school students and others among undergraduates: five student ideas are endorsed with equal frequency by both groups, while four are more prevalent among high school students and four among undergraduate students. This largely comparable prevalence of most student ideas between the two groups aligns with a broader line of research indicating that such ideas may persist not only among the undergraduate students in physics-related

programs prior to formal instruction, but even after targeted instruction in advanced university courses [51].

Of particular note is that undergraduate students show a significantly higher prevalence of specific student ideas frequently documented in the literature, particularly “sequential reasoning,” [3] “current consumption,” [16] and “voltage consumption” [4]. In addition, these students’ ideas appear to be more closely connected to everyday experiences and everyday language than those more common among high school students. For example, everyday language and experiences may contribute to the persistence of certain student ideas. In German, the commonly used term “current consumption” [52] may plausibly reinforce the idea that current is used up as students get older. Similarly, undergraduate students may rely more frequently on sequential reasoning, as intuitive conceptions related to flow and sequence can become stabilized through repeated everyday experiences in the absence of formal instruction [38]. In contrast, student ideas such as “no voltage in an open circuit” or the “inverse concept of resistance,” which are more prevalent among high school students, may be less likely to be associated with everyday experiences. As a result, such ideas may be less strongly reinforced outside formal learning contexts and may therefore be more readily addressed through conceptual reasoning at later stages.

Research question 2: How consistent are student ideas about simple dc circuits among high school and undergraduate students across different isomorphic items?

Overall, the study reveals low consistency in how students apply their ideas across varied items. In fact, fewer than half of the participants (and often fewer than one in four) who respond according to a student idea in one item do so in a second item, and only a fraction do so in a third item. This finding aligns with research indicating that students’ reasoning in physics is shaped more by contextual features than by coherent ideas [18,35,53–55]. Specifically, similar findings in the domain of electric circuits were reported before [4,56].

Moreover, a comparison of the two groups reveals that, overall, high school students and undergraduate students do not differ significantly in the consistency with which they express most of their student ideas. Two exceptions, however, are the student ideas that “current is used up” and that “voltage is shared between resistors connected in parallel,” both of which are held significantly more consistently by undergraduate students than by high school students. Referring back to the discussion at the beginning of this section, the tendency to justify answers in alignment with a student’s idea in the two-tier instrument—both in prevalence and in consistency across items—on a group level appears independent of age and academic level.

The student idea “current consumption” stands out, as it is not only more prevalent among undergraduate students but also expressed more consistently, including across all

three items. This pattern is consistent with the interpretation that everyday experiences and expressions (such as the term “current consumption”) may contribute to the stabilization of certain student ideas over time, as they are anchored in everyday language, in this case, German. Given that the undergraduate sample represents a positively self-selected group with higher overall conceptual understanding, the persistence of this idea appears particularly noteworthy. At the same time, it is important to emphasize that these findings do not provide direct evidence of developmental change over time.

At first glance, the observed low level of consistency might seem to contradict the knowledge-as-theory perspective. However, this perspective relates students’ framework theories to deeper ontological categories, which, “at the surface,” that is, when responding to multiple-choice items, may not be directly visible as consistent framework theories. From this standpoint, inconsistent responding suggests that students’ framework theories allow sufficient flexibility for context-dependent answers, while the constraints imposed by these frameworks often relate to deeper underlying ontological categories that may not be readily apparent at the contextual surface level [11]. In contrast, the knowledge-in-pieces perspective does not assume deeper and stable framework theories and explains inconsistent responding directly through the situational influence of surface features of the items.

B. Limitations

The present study compares student ideas across distinct educational stages based on a substantial sample, yet several methodological and conceptual constraints must be acknowledged. First, the data do not allow us to determine whether the observed patterns are better explained by the knowledge-in-pieces or the knowledge-as-theory perspective. Both perspectives offer distinct interpretations of the findings, which we have outlined in the discussion. Second, for the undergraduate cohort, we cannot fully account for what additional learning about electric circuits may have occurred since their formal instruction in grade 7. Moreover, this group was heterogeneous, comprising students from various degree programs, which could introduce variability that remains unresolved in our analysis. Another potential limitation concerns the different test lengths across both groups, as undergraduate students completed the full test booklet, whereas high school students completed only subsets of items. While longer testing times may in principle induce fatigue, empirical evidence suggests that within moderate durations of approximately 45 min, fatigue is primarily experienced subjectively and does not lead to measurable performance decrements [57]. Moreover, longer test forms tend to increase random measurement error rather than systematically bias responses [57], making a systematic

disadvantage of the undergraduate group unlikely. In addition, undergraduate students were older and can be assumed to possess more advanced cognitive and self-regulatory capacities, which likely further mitigated potential fatigue effects. We therefore assume that the different test durations did not meaningfully affect the reported results. Furthermore, the interpretation of results for the “sequential reasoning” student idea should be made with caution, as this item was assessed using a different high school student sample (group B). Given the large number of chi-squared comparisons, the unadjusted family-wise error rate is likely inflated. Accordingly, p values should be interpreted with caution. As the sample is limited to schools and universities from certain areas in Austria and Germany, the findings may not readily generalize to other educational systems, linguistic contexts, age groups, or disciplinary backgrounds. Our language-based interpretation, in particular, refers to German. Cross-linguistic replications are needed, as prior work suggests that in English, broader “electricity use” schemas are common, without explicit reference to “current.” A further limitation concerns the use of a two-tier multiple-choice instrument, which allows large-scale analyses of the prevalence of specific student ideas and associated response patterns but provides only indirect access to underlying cognitive structures. Accordingly, the reported consistency measures reflect response regularities rather than stable conceptual frameworks, and the findings should be interpreted as descriptive constraints for theoretical accounts rather than as direct tests of epistemological perspectives.

VII. CONCLUSIONS

In summary, this study offers a quantitative insight into the prevalence and internal consistency of well-documented student ideas in the domain of simple dc circuits. Examining how frequently and coherently these ideas occur across different educational groups offers empirical evidence that can inform and constrain the ongoing theoretical discourse with respect to the knowledge-in-pieces and knowledge-as-theory perspectives by providing large-scale empirical patterns of prevalence and consistency that theoretical accounts must be able to accommodate. With regard to student ideas, notable differences emerged between those that are more likely to be reinforced by everyday experiences, such as sequential reasoning or current consumption, and those of a more technical nature, which are less likely to be shaped by such experiences. The former tended to occur more frequently among undergraduate students than among high school students, suggesting that certain student ideas may be continuously influenced and reinforced by daily life contexts. This additional finding could serve as a starting point for more targeted studies that explicitly investigate this phenomenon.

Beyond these findings, the findings have implications for physics education practice: the high prevalence of student ideas among undergraduate students who have chosen to study a physics-related subject highlights the prevalence of these ideas well beyond secondary education. This underscores the need for evidence-based instructional designs [58,59] that foster conceptual change and strengthen conceptual understanding against the influence of everyday experiences.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [60].

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