CURRENT RESEARCH JOURNAL OF PEDAGOGICS (ISSN: 2767-3278)

VOLUME: Vol.07 Issue02 2026
DOI: - 10.37547/pedagogics-crjp-07-02-19
Page: - 82-87
RESEARCH ARTICLE OPEN ACCESS

Developing Conceptual Understanding Of Fundamental Physical Constants: A Framework For Student Competencies

Xamidov Botirjon Xusnidinovich

Basic doctoral student at Navoi state university, Uzbekistan

Received: 16 December 2025 **Accepted:** 07 January 2026 **Published:** 11 February 2026

ABSTRACT

Fundamental physical constants embody empirical regularities, anchor measurement systems, and permit predictive modeling in mechanics, quantum physics, and cosmology, making them unique in scientific teaching. They are often taught as static numbers to memorize and put into formulae, which can lead to shallow procedural fluency without conceptual comprehension. An empirically supported competency-oriented approach for building students' conceptual comprehension of fundamental physical constants is proposed in this article. The framework presents constants as structured notions with operational definitions related to measurement, dimensions to representations, epistemic status to theory and evidence, and modeling roles to invariance and scaling. We incorporated constant-centered learning sequences into lectures, problem solving, and lab work in basic university physics using a design-based research method, stressing dimensional reasoning, uncertainty, historical-instrumental settings, and computer modeling. Mixed evidence from pre/post assessments, written explanations, and semi-structured interviews suggests that students can view constants as constraints that connect models to the world, delimit regimes of validity, and support coherent reasoning about units, scales, and approximations. Results suggest arranging education around a few transferable competencies: representational fluency, metrological reasoning, epistemic interpretation, and model-based application. In conclusion, the author suggests curriculum design that aligns with present SI concepts and assessment tasks that evaluate conceptual progress rather than formula memory.

Keywords: Physical constants; conceptual understanding; student competencies; metrology; SI system; dimensional analysis; modeling; physics education research.

INTRODUCTION

People sometimes call fundamental physical constants the "fixed numbers of nature," which sounds stable but may also hide the mental work that goes into figuring out what a constant is, why it matters, and how its value is known. In physics, constants like the speed of light in a vacuum, the Planck constant, the elementary charge, the gravitational constant, and the Boltzmann constant link theory, measurement, and computation. They show up in equations that explain the basic ideas behind energy quantization, relativistic invariance, thermodynamic temperature, electromagnetic interactions, and gravitational dynamics. For physicists who work in the field, a constant is seldom just a number. It is an organizational idea that determines what counts as a measurable quantity, what changes keep laws the same, and what approximations are acceptable in a specific regime.

In most lessons, though, constants are often just numbers that are already in tables or in the front of textbooks. Students learn how to choose a constant, plug it into a formula, and figure out a number response. While this procedural technique might be beneficial, it may unintentionally foster a limited perspective that regards constants as external additions rather than essential components of modeling. Studies in physics education have consistently demonstrated that students may obtain accurate numerical answers while possessing tenuous or inconsistent conceptual frameworks, particularly when employing equation hunting and plug-and-chug methodologies. When students see constants as just tools for doing math, they might not relate them to dimensions and units, to physical meaning, to uncertainty, or to the epistemic basis of measurement.

In modern education, the necessity to comprehend constants on a conceptual level has grown stronger for at least three reasons. First, modern science and engineering need people to be able to use quantitative models in many situations, which means that students need to think about scale, units, and approximations instead than just memorizing formulae. Second, the modern International System of Units (SI) clearly specifies base units by using set numerical values for certain constants. This turns constants from reference numbers into definitional anchors of measurement. Third, computational and data-driven approaches are now an important part of studying physics. Constants are very important for determining scales, standardizing variables, and limiting simulations. These changes mean that constants should be taught not just as fixed numbers, but also as ideas that connect representation, measurement, and theory.

This article discusses how to organize lessons so that children may learn about basic physical constants in ways that can be tested, used in other situations, and are in line with how science is done today. The main point is that the best way to grasp constants is as a collection of skills rather than as a list of facts. Competencies delineate the practical applications of knowledge by students in genuine tasks, including interpretation, justification, modeling, estimation, and critique. A competence framework facilitates cohesive evaluation by delineating observable performances rather than assumed internal conditions.

The goal of this study is to suggest and test a framework for student capabilities in comprehending the basic physical constants conceptually, as well as to look at instructional design elements that help these competencies increase in an introductory university physics setting.

A design-based research technique was employed to create and enhance a competency-oriented framework and to evaluate instructional sequences that emphasize conceptual centrality of constants. Design-based research is suitable for creating theory-informed treatments in authentic educational contexts while continuously improving both the intervention and the foundational theoretical notions. The study was conducted in an introductory calculus-based university physics course comprising lectures, problem-solving recitations, and laboratory activities. The course included mechanics, thermodynamics, electricity and magnetism, and an introduction to current physics. This gave students many chances to use basic constants.

The participants were first-year college students who were taking the course. The group was made up of people who studied different things in engineering and the natural sciences. Taking part in research instruments was optional and had no effect on grades. Student work items were anonymised for examination.

The intervention included learning sequences that were spread out throughout the whole semester. Each sequence was made up of a few constants that were important to the issue at hand. Instead than only giving numerical values for constants, the lesson focused on four interrelated parts.

First, operational meaning was emphasized by connecting each constant to how it is measured or realized, taking into account the role of tools, experimental design, and uncertainty. Second, dimensional reasoning, unit analysis, and symbolic manipulation were used to create representational meaning by treating constants as bearers of dimensions that connect quantities. Third, we spoke about how constants come up in theories, how they limit models, and how their values are set and changed in scientific practice to come up with the idea of epistemic meaning. Fourth, the use of constants to define natural scales and help with estimate, nondimensionalization, and computational simulation made modeling meaning more important.

Learning activities encompassed guided problem-solving with clear prompts for unit and scale reasoning, laboratory tasks necessitating uncertainty propagation and calibration, and brief computational modeling assignments where constants were utilized to parameterize simulations or to validate the plausibility of outputs. These exercises were intended to be consistent across contexts, allowing students to see constants as recurring conceptual entities rather than isolated topic-specific items.

To assess the growth of competencies, many data sources were gathered.

Quantitative measures comprised pre/post-assessment items focused on dimensional reasoning, unit consistency, estimate, and the contextual interpretation of constants. The items were designed to need explanation and justification, so diminishing the probability that pupils might achieve success via mere formula replacement.

Qualitative measurements encompassed written elucidations from specific homework assignments and laboratory reflections, in addition to semi-structured interviews with a portion of the participants. The interview questions challenged students to explain what a constant means in an equation, why they chose certain units, how a constant affects the physical scale, and how they would fix a solution that abused a constant.

We used descriptive statistics and normalized gain estimates at the item and cluster level to look at the quantitative outcomes. Each cluster was made up of the competences we were trying to improve. An analytic rubric that matched the suggested competence framework was used to look at qualitative data. Responses were categorized to identify indicators of representational fluency, metrological reasoning, epistemic interpretation, and model-based application. Coding reliability was ensured via repeated calibration on a common set of replies and the resolution of differences via conversation. We improved the framework by looking at the collected data to see which competence descriptors effectively separated beginner reasoning from more expert-like thinking.

The analysis validated a system wherein conceptual comprehension of essential physical constants is articulated through four interrelated abilities.

Representational fluency is the capacity of pupils to understand a constant in symbolic, pictorial, and numerical forms. This includes being able to think clearly about dimensions, units, and how to change equations. In student work, evidence of representational fluency manifested when learners regarded a constant as a dimension-bearing object that maintains coherence across values, rather than as a separable numerical quantity. Students who showed progress utilized unit checks more and more as a way to reason, not only as a way to check their work after they had done the math.

Metrological thinking is when students can relate a constant to how measurements are made, how uncertain they are, and how idealized definitions and realizations work in a lab context. Students made progress when they spoke about how to get the value of a constant, what measurement limits mean for accuracy, and how uncertainty in a constant or in related measured variables affects findings. In laboratory reflections, more sophisticated replies elucidated calibration logic and rationalized the choice of constants, emphasizing crucial numbers and sources of uncertainty.

Epistemic interpretation denotes students' capacity to elucidate the rationale for the presence of a constant in a law, its implications for physical structure, and its connection to invariance, symmetry, or theoretical concepts. Students who underwent this transition began to express that constants can indicate borders between regimes or encode coupling strength, rather than serving only as conversion factors. For instance, while talking about the speed of light, students talked more and more about how it affects relativistic structure and causal constraints, not just how fast it is.

Model-based application means that students may utilize constants to build, test, and improve models. This includes things like estimate, scaling, nondimensionalization, and computational simulation. Evidence for this skill includes being able to pick the right constant for a modeling job, use scale arguments to explain why approximations are necessary, and figure out how altering a constant in a simulation would change the projected behavior. Students who created model-based applications utilized constants to evaluate plausibility and identify unrealistic outputs, considering constants as limitations on model behavior.

These skills were not separate from one other in the dataset. Students who enhanced their representational fluency had a greater propensity for model-based application, since dimensional thinking facilitated estimate and simulation verification. Metrological reasoning and epistemic interpretation mutually supported each other when students acknowledged that measurement definitions embody theoretical commitments and that theoretical frameworks influence what may be measured.

Comparisons before and after showed that students consistently got better at assessment questions that required dimensional analysis, unit justification, and scale-based estimate. Items that required an explanation of the presence of a constant in an equation exhibited moderate improvements, indicating that epistemic interpretation evolves more gradually than representational abilities under constrained instructional time. The most significant enhancements were observed in tasks requiring students to assess the plausibility of a calculated result using constants as benchmarks, suggesting that constant-centered activities facilitated a transition from mere procedural computation to interpretative reasoning.

Written explanations and interviews showed that students' vocabulary and thinking had changed a lot. Students frequently referred to constants as "given numbers" utilized "because the formula needs it" throughout the initial stages of the course, and they exhibited irritation when unable to recall a constant's value. Later, a lot of students said that constants "set the scale," "connect units," or "represent a limit." They also gave more and more reasons for their choices of constants based on the physical context.

A consistent qualitative indication of conceptual advancement was pupils' readiness to regard constants metaphorically for extended durations, deferring numerical replacement. Students who symbolically kept constants were more inclined to observe cancellations, discern dimensionless groups, and acknowledge when a result was contingent upon a ratio rather than an absolute value. This symbolic persistence seemed to help with transfer since students could apply the same reasoning framework in multiple situations without having to remember numbers.

Laboratory reflections demonstrated an enhancement in metrological thinking as students articulated constants in connection to unit realizations and the practical limitations of equipment. Students increasingly understood that constants do not eradicate uncertainty; rather, they relocate the point at which uncertainty infiltrates the measurement chain. This viewpoint assisted students in perceiving experimental inconsistencies as insightful rather than merely erroneous.

The results are in line with a bigger idea in scientific education: students generally have trouble understanding things that work on more than one level at the same time. A basic constant may serve as a measurable quantity, a definitional reference, a theoretical parameter, and a modeling instrument. Because it is supported by several common issue types, students can only look at it from one angle at a time, usually the computational angle. When education fails to elucidate multiplicity, students may develop fragmented knowledge that facilitates numerical response generation but hinders explanation and transfer.

Another source of difficulty is that constants are often presented without regard to epistemic inquiries. Students may come to think that constants are just random things in textbooks instead than the result of human research and experimentation. When students don't understand how constants are made, they might not understand why uncertainty is important, why values change from time to time, or why the same constant might show up in many different situations that don't seem to be linked.

Third, constants might seem abstract because they typically link numbers that pupils haven't yet put together in their minds. For example, the Planck constant connects energy and frequency, which means that students have to connect wave descriptions with particle-like interactions. Students need to connect statistical reasoning with thermodynamic state functions because the Boltzmann constant connects microscopic and macroscopic descriptions. Without proper scaffolding, constants turn into unclear tokens.

A competence framework can help with these problems by making clear what it means to have a conceptual knowledge in real life. Representational fluency means that teachers should regularly regard constants as things with dimensions and should make it usual for students to start their reasoning with symbols, units, and scales instead of just replacing numbers. This competence is best tested using tasks that allow students to rebuild an equation's units or find an inconsistency. These tasks make students think about how the constant fits into the equation.

Metrological reasoning suggests that laboratory and measurement-based activities must not to be divorced from theoretical learning. When students think about constants as the defining points of units, they may better comprehend how a measuring technique gives a definite number and how calibration and uncertainty fit into the picture. Aligning laboratory prompts with constant-centered questions facilitates this integration, for instance, by requiring students to defend which constants are presumed to be correct for a calculation and which uncertainties prevail in the final result.

An epistemic interpretation means that teaching should link constants to ideas like invariance, symmetry, and regime structure. This doesn't mean giving long history lessons, but it does mean giving pupils clear instructions that tell them to understand, not just calculate. When students elucidate the appearance of the speed of light in relativistic dynamics or the challenges in properly measuring the gravitational constant, they interact with constants as epistemic entities. Students' understanding of this is improved when they discover that constants may show how deeply a theory is committed to its structure.

Using constants as tools for estimating and testing models is what model-based application means. Computational assignments are especially useful here since constants readily show up as parameters in simulations. When students look at how changing a parameter affects projected behavior, they learn to link constants with physical sensitivity and regime changes. Even without calculations, estimate exercises may help model-based learning by making students utilize constants to figure out orders of magnitude and decide if something is likely to happen.

The competence framework is in line with the contemporary SI, which bases unit definitions on defined values of certain constants. This change is not just a change in how we measure things; it's also a chance to learn. When students understand that unit definitions are based on constants, they may see that constants are not distinct from measurement; they are an important part of it. Teaching students about this link can help them build a clear mental model in which theory and measurement limit each other.

It is also vital not to treat constants as if they are only definitional artifacts. A lot of constants are still decided by experiments, and even fixed constants become meaningful through the experimental techniques that put units into practice. The pedagogical objective is not to substitute one method of memory for another, but to assist students in understanding the concept of "fixed value" in both operational and epistemic contexts.

If conceptual comprehension is considered competency, testing must extend beyond only requiring pupils to recollect constant values. Good assessment assignments have students explain what a constant does in a model, defend their choice of units, guess what the right amounts may be, and think about what would happen if they used the wrong value or unit. The findings of this study indicate that tasks requiring symbolic persistence and dimensional thinking are especially diagnostic, since they demonstrate whether students perceive constants as structural restrictions rather than just number inputs.

The study was conducted in a singular course situation and hence cannot independently demonstrate generalizability across institutions and curricula. Furthermore, epistemic interpretation exhibited slower progress compared to representational abilities, indicating that more profound conceptual transformations may need prolonged teaching and frequent chances for elucidation and contemplation. Future research should evaluate the framework in various educational contexts, provide validated evaluation tools for each skill, and investigate long-term retention and applicability to advanced studies and transdisciplinary contexts.

Fundamental physical constants ought to be imparted as more than just numerals. When teachers provide constants as abstract ideas that connect measurement, representation, theory, and modeling, students may learn in ways that help them transfer what they know and think scientifically. The competence framework delineated above defines the conceptual comprehension of constants via representational fluency, metrological reasoning, epistemic interpretation, and model-based application. Evidence from design-based implementation in basic university physics suggests that constant-centered learning sequences can transition students from mere procedural replacement to more coherent reasoning about units, scales, uncertainty, and model constraints. This method is timely given the current SI and the increasing significance of computer modeling in physics education. A competence orientation also gives teachers a useful way to create tests and lesson plans. This lets them say what it means for students to grasp constants conceptually instead of just using them.

REFERENCES

1. Mohr P. J., Newell D. B., Taylor B. N. CODATA recommended values of the fundamental physical constants: 2014 // Reviews of Modern Physics. 2016. Vol. 88, № 3. P. 035009. DOI: 10.1103/RevModPhys.88.035009.

2. Mohr P. J., Newell D. B., Taylor B. N. CODATA recommended values of the fundamental physical constants: 2018 // Reviews of Modern Physics. 2021. Vol. 93, № 2. P. 025010. DOI: 10.1103/RevModPhys.93.025010.

3. Quinn T. J. From artefacts to atoms: the BIPM and the search for ultimate measurement standards // Oxford: Oxford University Press, 2012. 304 p.

4. Milton M. J. T., Williams J. M., Forbes A. B. The international system of units (SI) and the fundamental

constants // Philosophical Transactions of the Royal Society A. 2014. Vol. 372, № 2026. P. 20140038. DOI: 10.1098/rsta.2014.0038.

5. Stock M., Davis R., de Mirandés E., Milton M. The revision of the SI—fundamental constants and the future of the kilogram // Metrologia. 2019. Vol. 56, № 2. P. 022001. DOI: 10.1088/1681-7575/ab05d5.

6. Bureau International des Poids et Mesures. The International System of Units (SI): 9th edition // Sèvres: BIPM, 2019. 216 p. URL: https://www.bipm.org/en/publications/si-brochure (accessed: 18.12.2025).

7. NIST. Fundamental Physical Constants (online reference data) // National Institute of Standards and Technology. URL: https://physics.nist.gov/constants (accessed: 18.12.2025).

8. Redish E. F. Teaching physics with the physics suite // Hoboken: John Wiley & Sons, 2003. 216 p.

9. McDermott L. C., Shaffer P. S. Tutorials in introductory physics // Upper Saddle River: Prentice Hall, 2002. 274 p.

10. Hestenes D., Wells M., Swackhamer G. Force Concept Inventory // The Physics Teacher. 1992. Vol. 30, № 3. P. 141–158. DOI: 10.1119/1.2343497.

11. diSessa A. A. Knowledge in pieces // In: Constructivism in the Computer Age / Ed. G. Forman, P. B. Pufall. Hillsdale: Lawrence Erlbaum, 1988. P. 49–70.

12. Chi M. T. H. Three types of conceptual change: belief revision, mental model transformation, and categorical shift // In: Handbook of Research on Conceptual Change / Ed. S. Vosniadou. New York: Routledge, 2008. P. 61–82.

13. Hammer D. Epistemological beliefs in introductory physics // Cognition and Instruction. 1994. Vol. 12, № 2. P. 151–183. DOI: 10.1207/s1532690xci1202_4.

14. Brewe E. Modeling instruction: a contemporary approach to physics teacher education // In: Reviews in PER: Research-Based Reform of University Physics / Ed. E. F. Redish, P. J. Cooney. College Park: AAPT, 2007. P. 1–48.

15. Hake R. R. Interactive-engagement versus traditional methods: a six-thousand-student survey of mechanics test data // American Journal of Physics. 1998. Vol. 66, № 1. P. 64–74. DOI: 10.1119/1.18809.

16. Duit R., Treagust D. F. Conceptual change: a powerful framework for improving science teaching and learning // International Journal of Science Education. 2003. Vol. 25, № 6. P. 671–688. DOI: 10.1080/09500690305016.

17. Halliday D., Resnick R., Walker J. Fundamentals of Physics. 10th ed. // Hoboken: John Wiley & Sons, 2014. 1392 p.

18. Tipler P. A., Mosca G. Physics for Scientists and Engineers. 6th ed. // New York: W. H. Freeman, 2007. 1480 p.

19. Feynman R. P., Leighton R. B., Sands M. The Feynman Lectures on Physics. Vol. I–III // Reading: Addison-Wesley, 1964. 1560 p.

20. Maxwell J. C. A Treatise on Electricity and Magnetism. Vol. 1–2 // Oxford: Clarendon Press, 1873. 999 p.