Newton's Law- A Theory of motion or force?

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Abstract. Regular disciplinary instruction of introductory physics at high school often misses a holistic perspective of the subject matter, its structure and hierarchy. We have considered the domain of mechanics and provided such a perspective in a summative lecture by framing mechanics contents in discipline-culture framework. In the experimental teaching, we focused on Newton's laws of motion as the nucleus of classical mechanics. Considering mechanics as a culture, that is, addressing the debate with periphery conceptions, caused students to appreciate the fact that mechanics is about theory of motion, while forces present only a certain conception to account for it.

1. Introduction
Constructing meaningful knowledge and holistic understanding of the subject matter in learning science remains in the focus of research effort. Science traditionally seeks establishing structural knowledge, a theory, with hierarchical arrangement of its components. Scientific progress presents reconsidering of previous theories in conceptual contest [1] while regular teaching disciplinary course often presents scientific products univocally ignoring that debate. Researchers argue for the conceptual variation, learning space for the concepts to be understood [2]. The discipline-culture (DC) structure of a theory [3] preserves conceptual debate by addressing elements of peripheral knowledge in rival contrast with the clearly identified nucleus (fundamental concepts of the theory). Such knowledge was labeled cultural content knowledge (CCK) [4]. Creating CCK by means of a summary lecture was first applied as a delay organizer with regard to teaching optics at high school [5]. This study expanded the DC approach to teaching mechanics at high school. Mechanics is the first theory students' encounter in physics class. We will present some results of our study, the choice of contents of such summary lecture matching the format of discipline-culture, aspects of the impact on students' conceptual knowledge with respect to Newtonian theory as a the theory of motion.

2. Background
We have examined the textbooks commonly used in mechanics of 11th grade of our high schools [6]. College Physics [7] may serve as a parallel resource in English. The examined textbooks and allegedly the corresponding teaching, provide laws, concepts, models, experiments, applications, all sequentially unfolding from basic to a more advanced. A great amount of knowledge elements emerge to the learner. Emphasis is put on standard problem solving which supposed to provide understanding and ability to apply the knowledge in concrete situations, qualitatively and quantitatively. Yet, the textbooks do not arrange the concepts in somewhat hierarchical structure, beyond presenting the formal contents. Newton's laws are introduced expressing law regularity in terms of forces. There is no emphasis is given that the laws present a specific theory to account of motion. Even if some textbooks mention in the introduction that mechanics is about the “nature of motion” but their presentation, the context of Newton's laws mainly discuss forces as the cause of anything that happens to motion, thus placing force in the focus of discussion [8]. Such presentation of the continuously
growing range of knowledge without holistic framework and hierarchical structure produce an impression of learning as a simple accumulation: the more we learn the more we know. The students are left solely with intuitive ideas regarding relative importance of concepts, lacking a big picture of the subject matter. The promoted orientation of the class activities is toward the matriculation examination comprised of standard problems to solve. That normally leads towards instrumental understanding of physics.[9] The relationships between theory and reality, theory and models, laws and principles, validity limits, concept definitions – all together presenting the nature of the scientific knowledge – usually remain a subject of intuitive coverage only. No hint is usually provided as to how the presented knowledge was obtained, the contest of alternative accounts; why the concepts and conceptions we currently learn were preferred and others – dropped. Lacking appropriate organization in a fundamental theory of motion the learners frequently produce misconceptions regarding force-motion relationship.

3. Delay organizer based on the discipline-culture model
To upgrade the traditional teaching and introduce hierarchical organization of knowledge elements in a meaningful system, it was suggested to adopt triadic model for structure disciplinary knowledge and introduce its hierarchy and competitive ideas from the pertinent disciplinary discourse in the history of physics [4]. The triadic DC-structure included nucleus (basic principles and concepts), body (the derived theoretical and affiliated empirical laws, models, solved problems, experiments, etc.) and periphery (concepts alternative to the nucleus). The new structure provided the learners with the big picture of the subject matter in educational context. The instruction revealed hierarchical organization of the classical mechanics as a theory of motion.

The suggested classification of knowledge elements aimed to promote students' conceptual knowledge, the meaning of notions they learn. Such understanding is expected due to affiliating each item of knowledge to the certain type of the triadic structure, nucleus, body or periphery. The conceptual variation allows appreciation of conceptual meaning in several aspects, hierarchical, relational, and methodological. The status of knowledge elements of each considered element of knowledge was addressed. Such teaching causes meaningful learning of the nature of scientific knowledge – cultural content knowledge of the subject [3].

Questions arise regarding the ways to apply DC approach, pedagogical strategy to stimulate students' construction of CCK. Levrini and colleagues [5] introduced a summary lecture organizing knowledge of regular disciplinary course of optics in high school in terms of DC. The lecture served as a delay organizer. Here we report about the attempt to introduce and assess a delay organizer applied on teaching classical mechanics, the central domain in school physics which establishes foundation of physics knowledge and science in general.

4. The Experiment
In the first stage of the study, we prepared a summary lecture emphasizing the nucleus of mechanics in the school course of mechanics. The experiment comprised a lecture of 90 minutes (double period). The lecture touched on theory-nature relationship, area of theory validity, the status of principles, models, and laws in physics drawing on valid resources. We introduced the DC perspective to mechanics curriculum. Following the review of high school textbooks we constructed a summary lecture through identification of the basic components of nucleus and body as presented at schools. We added a few corresponding elements periphery. We, then, applied the experimental teaching to a representative sample of the student population (11th and 12th grades) and preservice teachers of science from an educational college. The knowledge of the participants was assessed.

The experiment included a sequence of pre-test questionnaire, lecture of about 90 minutes (double period), post-test questionnaire, class discussion a week after the lecture and a few clinical interviews with the individuals chosen for their verbal skills shown in the discussion.

The questionnaire was designed in open-question format given the novelty of this teaching and lack of information about possible impact of this type of contents. The questionnaire included the questions
used in the previous studies [5] where they showed their validity and effectiveness. Our research questions addressed the following aspects:

1) The holistic perception of classic mechanics;
2) Probing of basic elements of scientific knowledge (concepts, theory, laws, models);
3) Conceptual understanding of some problems in mechanics;
4) Understanding of theory validity/correctness in physics;
5) The meaning of being proved in physics;
6) Alternative conceptions in mechanics;
7) Students’ confidence.

Some of these dimensions were added following the classroom discussion. They were included only in the post-instructional questionnaire and the interviews. Each topic was probed by more than one question to enhance the reliability and reveal a more refined picture of students’ knowledge using triangulation approach. The questionnaires were administrated in a regular class environment in 40 min. periods. The experiment was performed at the end of the study year during which mechanics was taught.

5. Format of the experiment

Our sample (Table 1) included participants from four classes of upper secondary school (11th and 12th grade) and two groups of preservice science teachers (educational college).

Table 1. The sample of the study

| Groups                        | Code  | Participants number |
|-------------------------------|-------|---------------------|
| Teachers (college 1)          | T1    | 13                  |
| Teachers (college 2)          | T2    | 7                   |
| Grade 12 (dedicated)          | S12d  | 10                  |
| Grade 12 (regular)            | S12r  | 23                  |
| Grade 11 (dedicated)          | S11d  | 8                   |
| Grade 11 (regular)            | S11r  | 13                  |
| Total                         |       | 74                  |

To increase representativeness the sample comprised classes from two most spread types of schools, regular and dedicated to sciences. College students were from different areas of the country. All groups were taught by different teachers. Yet, the classes were checked to be similar with respect to their heterogeneous social background and learning achievements making the sample representative for student population of the country. The experiment covered an academic year during which, teaching, observations, class discussions, assessments and data analyses took place.

6. Lecture contents

The challenge of comprising summary lecture was significant. Apparently, we had to address only the most important elements of knowledge in classical mechanics. In the DC structure, that implied the focus on Newton's laws of motion – belonging to the nucleus of classical mechanics. These contents were contrasted with the alternatives – the Aristotelian and medieval accounts of motion of the periphery of the classical mechanics. The lecture addressed the First Newton's Law of motion as the central conception of classical mechanics defining the uniform motion as a natural state of a body, a subject for change under the influence of the external force applied on the body [8]. The Second Newton's Law was introduced as a quantitative refinement of the First Law, and the Third Newton's Law was introduced to facilitate the expanding of the account to several bodies in interaction. The summary, thus, emphasized the central importance of the First Newton's Law, in contrast with the teaching considering it as a special case of the second law [10].
The presented Newtonian paradigm included the concepts of point masses, state of motion, instant velocity and acceleration, force as the cause of continuous change of motion state, inertial mass, central interaction of masses at a distance – gravitation, absolute and mutually independent time and space. Furthermore, the students found the concept of mechanical energy and its conservation in mechanics as elements of the body knowledge deduced from the nucleus – Newton’s laws of motion. Fig. 1 displays the aspects which were associated in presenting the First Newton’s Law.

**Figure 1.** Newton's First Law as a context to address central aspects of classical mechanics

As mentioned, DC organization obliged to address the conceptual accounts of motion alternative to that of Newton – the periphery. Thus, we mentioned the Aristotelian dichotomy of natural and violent motion and their law-like regularities expressed in modern form and exact parallel with the Second Newton's Law. The medieval theory of motion – the theory of impetus was addressed as the second alternative conception of motion. The struggle of Galileo, Descartes and Newton with these two alternative accounts of motion were mentioned establishing the enlarge space of learning of the classical account. Inertial mass was introduced as representing resistance to the change of motion state in contrast with the previous understanding as the “resistance to motion” (preserved as a misconception).

The limits of validity of classical mechanics were elaborated determining the meaning of “correct” with regard to classical mechanics. In accordance, the status of being proved was defined as a procedure of displaying coherence of a claim or solution with the tenets of the considered theory, in our case – classical mechanics. The presentation addressed the concept of models and their types distinguishing among the models in the nucleus (such as point masses, instantaneous interaction), body of knowledge (such as the account of motion on inclined plane, simple levers, mathematical pendulum) and periphery (such as Aristotle’s positional weight, natural and violent motion, medieval dispersed impetus).

The massage of the summary was that classical mechanics introduced a specific account of motion and rejected others under certain assumptions encouraged students to revaluate their own understanding and organize the pertinent knowledge in a new way. The DC organization allowed them to identify other conceptions as contradicting classical mechanics, either obsolete or belonging to other theories (quantum and relativistic mechanics).

**7. Data processing**

The prior- and post-intervention assessment provided us with rich data analysed qualitatively and quantitatively. Within the qualitative analysis, the students' answers were processed in several steps. Firstly, students' answers, their explanatory patterns or strategies employed were grouped in categories.
considered characterising students' conceptual knowledge of mechanics. The grouping allowed us to
elicit students' representative views on classical mechanics. Portraying their conceptual and
procedural knowledge could indicate the impact of the applied teaching.

Within the quantitative analysis of the data, achievement score was ascribed to students’ performance
prior and after the lecture. Separation of the scores indicated the impact of the instruction in specific
dimensions specifying the total change. The quantitative results complemented the inferences
regarding effectiveness of the applied teaching beyond episodic changes.

8. Findings
Qualitative results
We mention here several categories characterizing students' knowledge in the perspective of
conceptual validity and exemplify each of them by illustrative quotation.

- Relationship of concepts within and out of classical mechanics:
  It [the summary] related among what we learned in mechanics, tied the concepts together.  
(S11d-7 T1-9)*
  It helped me to know what is Newton’s theory comparative to that by Einstein, and the reason 
we use one instead of the other in each case. (S12r-4)
(*) the codification indicates the sample group (Table 1) and the participant in the group

- Newton’s Laws — a theory of motion or force:
  The classical mechanics is a theory of force and its type of forces (S12r-14).
  The First Law states that only force is the reason for motion and only lack of force is the 
reason for conservation (S12r-19, S12r-23, S12d-2, S12d-9)
  The First Law works only for balanced bodies. (S11-r5)

- The impact of the lecture in the eyes of students:
  The lecture surprised me, opened my eyes and changed my conception of motion (S12r-7).
  Knowing how Newton stated his second law and the form Euler provided to it helped me 
understand how things emerged, made me comfortable with the formulas. (S12r-12)
  It was very good to tie formulas, fit them together with theories. (T1-15 S12-r4)

- Insufficiency of regular teaching:
  To be able to answer we need to learn lots of “stuff” more… (S12r-9)

- Students’ need of structural perspective:
  This structure helped me to arrange the known and order it all in my head. It was good…  
(S11r-3)
  An inclusive big picture is very important to us. It is something that can help us to 
understand the course. (T1-20 S12r-13)
  We are able [now] to organize the material and that helps us to understand Newton's laws. 
(S12r-13, S11d-4, S11d-4)

- Appreciation of periphery (obsolete theories):
  The example of the knowledge which was removed to periphery but returned back to nucleus 
was very impressive. (S11r-4)
  It was good to see different views on the same thing [subject] (S12r-4)
  It’s very important to know from where the wrong concept comes, what it relied on… so we 
can get rid of wrong understanding… (T1-5)
  Knowing about the “other” knowledge helped us to learn and clarify our understanding. 
(S11d-11, T1-7)
  Due to the old ideas we learned what is more important and what is less. (S12r-21 T1-28)

- Periphery as making misconception a serious issue instead of embarrassing matter:
I know how to solve problem but still feel that motion have something like internal force to move it. I know now that it is a wrong idea but couldn’t resolve the conflict. The lecture clarified it to me, especially the notion of state of a body (S12d-9).

- Appreciation of knowledge genesis:
  
  We talked before on Newton’s First Law but still, it was like floating, we never connected it to anything, now I see the connection. (T1-9)
  
  The understandings how things develop helped me feel comfortable with the law formulation. (T1-15)
  
  I liked the history of how the notion of atom moved from nucleus to periphery and then, later, back to the nucleus. (S11r-4)

- Triggering students’ curiosity and interest:
  
  [Enjoyment] It was very interesting and overall it’s good to learn new things. (T1-14)
  I don’t really like physics but I found the lecture very interesting. (T1-1)
  
  [Enrichment, imagination, solidarity, getting narrative] I like the historical anecdotes at side of the lecture its increase my curiosity on histories fact (S11d-8, S12r21, T2-1)
  I would like to know also about physicist’s background and their relationship with culture and knowledge evolution (S11d-7 S11r7, S11d-8)

  [Surprising, new perspective] The summary showed us a different perspective from that we were regular in physics class. (S12r-13)
  Aristotle’s definition of force and mass as resistance for the change of state was of a real surprise. (S12d-9)

  [Getting self-confidence, removal of tension] It helped me not to fear from physics classes... well done. (T1-3)
  It changed my perception of physics... I also feel more confident with the wrong concepts that can help (T1-15, S12r-4)

  [The summary] emphasizes and contrasts the right theories. Thanks for that. (T1-11, S11r-9)
  “Elements relation” was very interesting and helped me feel better with what we learned already. (T1-15)

  [Stimulating learning] The lecture enabled me to criticize knowledge and develop my own view on the material we learned in the class (S11d-7)
  It guided my reviewing of previous understanding (S12r-4)
  ...as it helps to examine physics knowledge in different ways and creates interest in deeper understanding of the whole picture (S11d-12)

- Cognitive resonance of teaching and students learning (location in ZPD, Vygotsky, 1986)
  
  Actually, things were familiar to me, but I did not know being asked about them before (T1-1)
  
  I understood it, I don’t know how to explain but I felt it (S12d-9)

  Because we already knew the stuff, it’s not that we don’t know... but lots of things were intuitive (S12d-9.1, T1-23).

9. Quantitative aspect

We may exemplify the outcome of the quantitative assessment by showing the change of students’ scores in several aspects important for evaluation of conceptual knowledge of mechanics. Table 2 presents the evaluation of answers to the twenty questions of the pre and post questionnaires after analysed with respect to better or new understanding following the summarizing lecture. The final scores and improvement (the increase of score) are displayed.
Table 2. The change of students' knowledge following summary lecture

| Quest # | Aspects of knowledge                                      | Score (post) | Improvement |
|---------|-----------------------------------------------------------|---------------|-------------|
| 1       | Appreciation of the agenda of Classical Mechanics         | 94%           | 6%          |
| 2       | Relationship between reality and theory in science        | 86%           | 43%         |
| 3       | Relationship between observation and inference            | 69%           | 46%         |
| 4       | Understanding of tentative and certain knowledge of science | 77%           | 14%         |
| 5       | Distinguishing between objective and subjective knowledge of science | 74%           | 29%         |
| 6       | Appreciation of scope of validity for physics theory     | 54%           | 6%          |
| 7       | Appreciation of plurality of scientific method            | 46%           | 4%          |
| 8       | Importance and role of alternative conceptions            | 91%           | 20%         |
| 9       | Understanding inertia as preserving state of motion       | 91%           | 3%          |
| 10      | Understanding reason for motion change                    | 69%           | 20%         |
| 11      | Understanding state of motion and the concept of momentum | 69%           | 29%         |
| 12      | The idea of natural motion                                | 71%           | 29%         |
| 13      | The equivalence of rest and motion                         | 91%           | 26%         |
| 14      | Understanding the meaning of mass                         | 97%           | 63%         |
| 15      | Understanding the meaning of force                         | 69%           | 14%         |
| 16      | Understanding acceleration in curved motion                | 74%           | 3%          |
| 17      | The status of Newton's first law                           | 57%           | 20%         |
| 18      | The meaning of Newton's third law                          | 97%           | 49%         |
| 19      | Using the third law in motion                             | 37%           | 23%         |
| 20      | Understanding the concepts of momentum and "internal force" | 60%           | 5%          |
| All     | Mean improvement of all                                   | 71.1%         | 22.1%       |
| All     | Std Deviation of all (Before After)                       | 13.95         | 16.5        |

\( p < 0.01 \) Statistically no significant difference \((p > 0.05)\)

We tried to record a wide range of impact which could be interested as delayed organization of knowledge. Our counting may start with the mature perception of mechanics fundamentals (Newton Laws) and proceed to the features of NOS interwoven together in Table 2. Such holistic perception was manifested in combination of conceptual understanding of some particular problems in mechanics.
with understanding of physics theory in general, validity/correctness of physical knowledge with students' confidence. Yet, since after all, the impact on the knowledge of mechanics was central for the experiment we may present the elicited change of students' knowledge in this perspective. Table 3 presents some pertinent evaluation results regarding students' knowledge of Newton's laws and some of their closely related concepts.

**Table 3. The assessment of knowledge change**

| Quest # | Aspects of knowledge                  | Score (post) | Improvement |
|---------|---------------------------------------|--------------|-------------|
| 9       | Second law, inertia as preserving motion | 91%          | 3%          |
| 15      | The meaning of mass and force          | 69%          | 14%         |
| 17      | Newton's first law necessity           | 57%          | 20%         |
| 18      | Justification of Newton's third law    | 97%          | 49%         |
| 19      | Using the third law in motion          | 37%          | 23%         |
| 20      | Understanding the concepts of momentum | 60%          | 5%          |
| All     | Mean improvement                       | 68.5%        | 19%         |

* p < 0.01 Statistically no significant difference (p > 0.05)

**10. Discussion**

The results of our experiment testified for the positive impact of the performed specific teaching in several important aspects. Those included understanding of relationship among specific concepts of mechanics and their status as elements of knowledge. Those included variety of features identified in the literature as Nature of Science. They included appreciation of knowledge structure and the knowledge of alternative accounts of motion (periphery), which especially triggered students' curiosity and interest. We were also evident to the effective impact of the lecture in the form of increasing students' self-confidence and desire to continue learning physics. To all these aspects, we have received qualitative and quantitative support.

The finding of the qualitative analysis of a strong tendency to consider force concept as the central agenda of the theory of mechanics is indicative. There is, thus, a great difference between the historical ambition to account for motion on behalf of physicists as philosophers of nature and considering classical mechanics as a theory of forces on behalf of novice students oriented to the pragmatic aspect of problem solving. The latter is not incorrect, but rather misses the tremendous diachronic program of physics to reveal the nature of motion. It started in the first physics treatise – Physics by Aristotle [11] and culminated, but not finished, in Newton's Principia and specifically in Newton's Laws [12]. The isolated focus on forces which are only a milestone on the way, an episode in the grand picture, "allows" students' such misconceptions as force is the cause of motion, no force – no motion (S12r-19), force-speed proportionality [13] (S12d-2.2), force is converted into motion and vice versa, and action-reaction equality is valid only to "balanced" bodies.

Revealing students' misconceptions regarding Newton's Laws as a theory of force shouldn't surprise. Losing the concept of motion state in student understanding of the First Law, makes it solely the "forceless case" and paves the way to the understanding of force as the cause of motion and motion as manifestation of force. It also provokes reducing conservation of the "quantity of motion" (momentum) solely to the lack of force, thus missing the concept of (uniform) motion as natural state of physical entities in classical physics [8] and the true origin of conservation laws [14].

Physics textbooks often limit their elaboration of Newton's Laws to the tools of practical value, making force in focus of any account, promoting algorithmic procedure of problem solving. This way, students indeed gain confidence in problem solving. Force concept takes the lead in any mechanical
treatment [13]. In practice, it is not easy to find a textbook with broader perspective elaborating the conceptual picture in which introduction of force was a solution of the account of motion by Newton's laws. Our presentation presented force only as a possibility chosen by Classical Mechanics, while modern and old physics treat motion differently.

The conceptual understanding of the Third Law by our students prior to the lecture was found also deficient. Application of the law in static state was different from dynamic situations, leaving alone that students could not justify that law. The original straightforward and simple proof provided by Newton drawing laws was shown at the lecture.

At the same time, our quantitative analysis revealed a clear positive impact of teaching the DC organized perspective on mechanics beyond individual scale, for different types of students. Indeed, the 19% improvement and expose students conceptions before the applied summary lecture. Tables 2 and 3 provide the initial evidence of the impact some dimensions of knowledge. The basic conceptual knowledge of mass and momentum showed improvement. We may add, however, the observation that the good students started with good knowledge of the Second Law, did not get much gain in their competence in problem solving.

Our approach refined general claims of the need to teach less but thoroughly, to make physics teaching representative and interesting, relate it to general context [15]. We pointed to the particular contents of such claims which otherwise remain vague and even misleading.

11. Conclusion

Altogether, the delay organizer in the form of summarizing lecture drawing on DC structure of physical theory helped students to understand the conceptual meaning of classical physics. It revealed the hierarchical organization of the subject matter in terms of tripartite structure nucleus-body-periphery. This study implies the need of a corresponding change in the design of physics curriculum in general, adopting DC structure. It has been demonstrated that even a summarising lecture may foster holistic perspective on the disciplinary knowledge, appreciation of its hierarchical organization at high school education. Summary lecture of the particular kind acts as an organizer and introduce delay organizer of knowledge and presents a feasible way to reach meaningful learning. The experiment had remedial impact on the common misconceptions of force-motion relationship as well as students' recognising Newton's Laws as theory of motion rather than forces. Though the latter may not influence problem solving, it may improve general understanding of mechanics required in further studies of other theories of physics, such as quantum and relativistic mechanics. Students obtained a chance to grasp the features of scientific knowledge rarely discussed in physics class: the theory based nature, modelling, laws, principles, validity area, the status of "being proved" in science, and the idea of conceptual genesis of knowledge. We consider this results being significant for the ongoing debate on the nature of scientific knowledge [16] seeking normative contents to adopt in science/physics education.

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