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ABSTRACT

There is a need to integrate the segregated perspective underlying research on scientific conceptions. Insights from scientists can provide information about the essential components of ideal knowledge. The purpose of this study was to investigate how researchers and teachers deal with scientific explanation. Three research physicists and five secondary physics teachers were asked to explain the Newton's Cradle demonstration. Written answers and follow up interviews were analyzed. All the respondents viewed the events as a series of collisions and related the phenomenon to the concepts of energy and momentum; however the arguments proposed as explanations differed in depth and in complexity. Results suggest that the differences in performances were related to: (1) the perceived purpose of the explanation and its nature; (2) the number of paradigms invoked for possible ways to describe the events; (3) the specification of assumptions underlying facts or data statements; (4) the examination of assumptions made to determine initial conditions; (5) the choice of variables and unknowns; (6) the proper application of scientific principles; and (7) the assessment of the entire argument in view of the acceptability of the underlying model and assumptions. Contains 29 references. (Author/LZ)

How Research Physicists and High-School Physics Teachers Deal with the Scientific Explanation of a Physical Phenomenon

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Abstract

The purpose of this study was to investigate how researchers and teachers deal with scientific explanation. Three research physicists and five secondary physics teachers were asked to explain the Newton's Cradle demonstration. Written answers and follow up interviews were analyzed. All the respondents viewed the events as a series of collisions and related the phenomenon to the concepts of energy and momentum; however the arguments proposed as explanations differed in depth and in complexity. Results suggest that the differences in performances were related to: (a) the perceived purpose of the explanation and its nature; (b) the number of paradigms invoked for possible ways to describe the events; (c) the specification of assumptions underlying facts or data statements; (d) the examination of assumptions made to determine initial conditions; (e) the choice of variables and unknowns; (f) the proper application of scientific principles; (g) the assessment of the entire argument in view of the acceptability of the underlying model and assumptions.

How Research Physicists and High-School Physics Teachers Deal with the Scientific Explanation of a Physical Phenomenon

INTRODUCTION

As part of a larger study aimed to describe teachers' and physicists' scientific conceptions, the purpose of this study was to investigate how research physicists and secondary physics teachers deal with the scientific explanation of a particular phenomenon.

Background

In the past, conceptions' research in science and mathematics education proceeded under three different traditions: Piagetian epistemology, philosophy of science, and systematic errors. (Confrey, 1990). Meanwhile, research on problem solving proceeded in a separate tradition, essentially based on the expert-novice paradigm in specific disciplines. New trends in conceptions research suggest adopting a more integrative view on understanding. (Posner & al. 1982, Posner & Strike 1985, Viennot 1985, Novak 1987, Perkins & Simmons 1988, Reif & Larkin 1991, Songer & Linn 1991, Duschl & Hamilton 1992.) This study is situated in these trends. It builds particularly on Posner & al.'s views on conceptual change and on Perkins & Simmons's integrated frames of understanding model. According to this model, deep understanding consists of a web of declarative, procedural and strategic knowledge embedded in four integrated frames: the content frame, the problem solving, the epistemic frame, and the inquiry frame. The kind of knowledge and characteristic tasks associated with each frame are described in Figure 1.

	Definition	Characteristic task
Content Frame	**facts, definitions, and algorithms** associated with the "content" of a subject matter	• **Recall facts** • **Use correct scientific vocabulary**
Problem Solving Frame	domain specific and general **problem solving strategies**	• **Solve textbooks and qualitative problems**
Epistemic Frame	domain specific and general **norms and strategies concerning the validation of claims** in a domain	• **Giving evidence, explaining rationales, and proposing tests of claims**
Inquiry Frame	domain specific and general **beliefs and strategies** that work to extend and to **challenge the** knowledge within a particular domain	• **Critical and creative thinking that questions the boundaries** of the domain

Figure 1: The framework for scientific understanding adopted from the article *Patterns of Misunderstanding* (Perkins and Simmons, 1988)

This investigation was based on the view that knowledge from the four frames is interwoven in the claims and strategies displayed through the performance of scientific tasks.

Significance

- What can we learn about scientific understanding?
- What can we learn about teaching knowledge?
- Are there implications for school science and the intended curriculum?

The intended curriculum

Constructivistic theories of learning tell us that students' existing conceptions interact with new knowledge and affect their learning. However, the knowledge transformations that occur in the process of learning are only the last link in a chain of transformations that occur in the curriculum process.

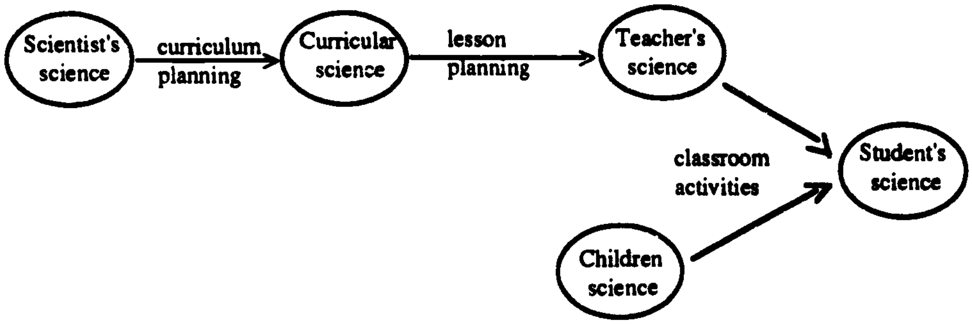


Figure 2: Transformations of scientific knowledge in the curriculum. (Adapted from Gilbert, Watts and Osborne. 1985. p. 12 in Pines and West Eds. Cognitive Structure and Conceptual Change)

Lack of studies on teachers' knowledge of their discipline

Although the effects of teachers' knowledge and views of science on their work have been well documented (Carlsen, 1989; Duschl & Wright, 1989; Brickhouse, 1990; Gallagher, 1991; Guess-Newsome & Lederman, 1992), the studies that investigated teachers' content knowledge are situated in teaching contexts,. They naturally emphasize the pedagogical aspects of knowledge, and fail to address the less pedagogical areas of scientific knowledge. According to Shulman (1986) this omission of the content-disciplinary knowledge from a research agenda on teaching has unfortunate consequences: researchers forget the importance of content and policy makers define standards that lack any reference to the content dimension.

Need to apply an integrated perspective on knowledge

Regardless of the age and role of individuals (children, students, teachers, or others), studies on scientific conceptions rarely apply an integrated perspective. In the past, one type of studies focused on the content frame, investigating knowledge of specific scientific concepts and theories. Another area of research focused on problem solving in the expert-novice tradition for specific sciences. This is illustrated for example by the organization of the recent *Handbook of Research on Science Teaching and Learning* (Gabel, 1994). Finally, studies on the nature of science addressed the epistemic frame and the inquiry frame from a different but similarly narrow point of view. The investigations of individuals' views of science and epistemic beliefs (summarized in Lederman, Gess-Newsome, & Zeidler, 1993) referred for the most part to general claims about the nature of science, about scientific theories, about evidence, or about inquiry procedureswith no reference to specific examples in a particular domain.

Previous studies had suggested that research in science and mathematics education could benefit from an integrated perspective. Viennot (1985) suggest consolidating the fields of problem solving and conceptual understanding as they are two facets of the same thing. Stewart & Hafner (1991) proposed extending the conception of "problem" in problem solving research.

There is a need to integrate the segregated perspectives underlying research on scientific conceptions. Insights frcm scientists can provide information about the essential components of ideal knowledge. Insights from teachers could highlight some of the implicit features of this knowledge. This study investigated the application of scientific conceptions in a particular situation, considering them as part of the understanding of the specific concepts invoked in the scientific inquiry of a physical phenomenon.

DESIGN AND PROCEDURES

Due to the nature of the qualitative study, the design became fluid. Purposive sampling, questioning strategies and the investigator's perspectives were reexemained at different phases of this inquiry.

Participants

The sample of informants included 15 participants altogether.

- 3 Research Physicists (R1-R3)
- 7 High School Physics Teachers (T1-T7)
- 2 Physical Science Teachers (PST1-PST2)
- 3 Doctoral candidates in Physics (D1-D3)

The second part of this study focuses particularly on six of them (T1-3, R1-3), but all responses contributed to establish the reference frame from which the responses were analyzed.

Data gathering and analysis

Assuming that epistemic beliefs and world views are integrated in the application of specific concepts, scientific explanation of a physical phenomenon makes a natural task for an individual to demonstrate these features of their scientific conceptions. The written questions were modeled after the Demonstrate - Observe - Explain (DOE) task described in Champagne, Gunstone, & Klopfer (1985). The respondents were given the apparatus known as "Newton's Cradle" with open ended questions asking to explain two specific instances of its behavior and to discuss their explanation. There was no time constraint or any limitations on the settings. Respondents returned the written responses at their convenience.

The data consisted essentially of written answers and tape-recorded interviews. Using a qualitative research approach, the follow-up interviews were planned according to the preliminary data analysis of all the responses gathered so far. The written responses and taped interviews were transcribed and analyzed according to the Strauss & Corbin (1990) coding and adjunctive procedures. A baseline representing the type of expected responses was established as reference frame for analysis of the individual explanations. The anticipated range of responses was based on the Hempel and Oppenheim (1988/1948) deductive model (D-N model) of scientific explanation.

$C_1\ C_2, \ldots C_n$	Statements *describing* the particular case as a series of independent two-body collisions.
	The initial state of each sphere is *given* in terms of mass and velocity
$L_1\ L_2, \ldots L_n$	Statements of the *applicable* rules are represented by equations of the two laws of conservation (momentum and energy) applied to this case.
DEDUCTING PREDICTION	The final state of each sphere is computed by solving equations and is shown to *match* the observation that one sphere takes off when only one was released, and two spheres take off when two spheres were released.

Figure 3 Adaptation of the deductive-nomological (D-N) model for scientific explanation (based on Hempel, 1966).

As the responses were analyzed, new questions were raised and the study design was modified. In some of the responses the task of scientific explanation was treated in ways that were not anticipated. Part 1 of the findings deals with the phenomenon of "out of range responses". Part 2 describes what constituted an explanation for selected participants: three researchers (R1, R2, R3) and three high school teachers (T1, T2, T3).

FINDINGS PART 1. WHAT DOES IT MEAN TO EXPLAIN? PERCEIVED PURPOSE AND CONTEXT OF THE EXPLANATION TASK

Baseline and expectations for the purpose and context of explanation

According to the investigator's reference frame, the expectation was that scientific explanations for the phenomenon (that "only one/two spheres took off when one/two spheres were released") presumed the explainer and the explainee to share the common grounds and ways of understanding which are associated with introductory level physics. At this level, the shared meaning to the task of *explaining a specific phenomenon* implies making attempts to derive particular observations from the application of appropriate laws of physics. The expectation was then to receive D-N like arguments, in which the descriptive statements, the choice of scientific laws, their application, and the validity of the entire process may vary.

However, written responses and subsequent interviews indicated that there were different ways for the *Explainers* in this sample to situate the explaining task in a context, to define their role, and to address the interplay between *Who explains*, *What is explained*, and *to Whom*. Written responses indicated that participants held different meanings and notions for interpreting the task of scientific explanation. Each respondent made different assumptions regarding the *purpose* the explanation and the *criteria* for a satisfactory explanation. Not all of these assumptions were explicit.

Analysis: Framework for the purpose and context of explanation

The following organizing scheme emerged from the diversity of roles and presumed situations found in the responses. With some simplification, the role assumed by each respondent as explainer could be described in reference to three extreme ways to define the identity they assumed as explainers. the Teacher's extreme ID (XTe), the Learner's extreme ID (XLe), and the Researcher's extreme ID (XRe). Table 1 outlines the characteristics of the *who*, *what*, and *to whom* as interpreted by each extreme ID.

Who explains?	XTeacher (XTe)	XLearner (XLe)	XResearcher (XRe)
explains What?	Explains concepts from school science topics in which the demonstration is used: e.g. *energy*	Explains the phenomenon, i.e. *why only one/two spheres take off ...*	Explains the phenomenon, i.e. *why only one/two spheres take off ...*
explains to Whom?	Explains to students in currently taught classes	Explains to self or to a peer who shares knowledge of concepts and procedures.	Asks for clarification about the explainee, desired level, amount of details and depth.

Table 1: Characteristics of each extreme interpretation of the explain task: roles, perceived purpose, and presumed settings

According to this idealization, an explainer of the extreme XTe type situates the task in a teaching context. The rules, the roles, and the goals are to develop a teaching explanation of scientific concepts through experimental demonstrations. An explainer of the extreme XLe type presumes a self-challenging situation, in which the goal is to predict the phenomenon by solving a physics problem. Rather than presuming a context, an explainer of the extreme XRe type asks for specifications about the task, its purpose, the scope, the amount of details, the depth, and other information in order to reduce the multiple scenarios that come to his/her mind. This framework allows to describe how the participants in this study conceptualized scientific explanation, how they proceeded, how they defined the problem, and how they dealt with it. The three extremes are represented as the vertices of the triangle shown in Figure 4.

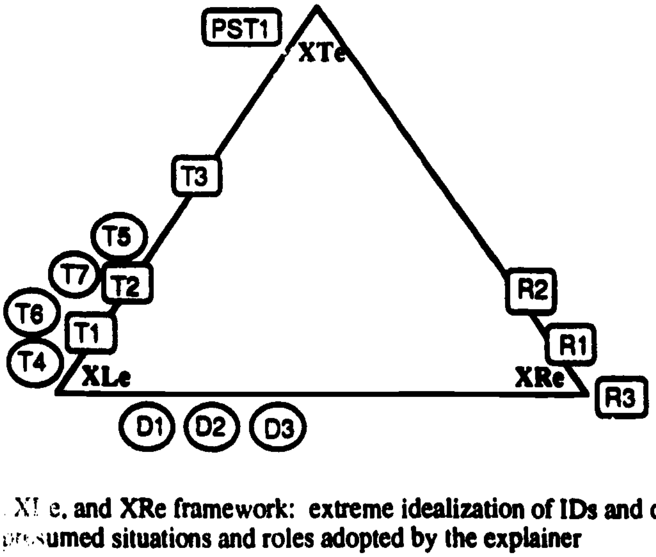


Figure 4: The XTe, XLe, and XRe framework: extreme idealization of IDs and distribution of responses according to the presumed situations and roles adopted by the explainer

Responses from the participants were described on a continuum along the sides of the triangle according to the ways they determined *what* was to be explained and *how* to develop the explanation. Seven cases were selected to represent the combinations suggested by this representation. They were: PST1, T1, T2, T3, R1, R2, R3.

Individuals' interpretation of the explanation task : presumed purpose and context

In most of these cases, the explanatory ideals and the logical character of the explanations was clearly consistent with the expected type of explanation (D-N model). Most of these respondents viewed the experimental observation as the target of the explanation. Also, they associated the notion of scientific explanation with the task of theoretical prediction. However, PST1's and T3's assumptions about *what should be explained* and to *whom* was more ambiguous. Four groups were identified according to the apparent perceptions of their roles explanation task. (PST1) (T3) (T1, T2) (R1, R2, R3)

PST1: a single identity, a single way to define the context

PST1 appeared to conceive of a teaching context as the only possible settings for explanation. She seemed to spontaneously assume the role of teacher (of a specific course) even when reminded that the questions were not about teaching but about her individual conception. The only type of explanation she conceived of was pedagogical.

> "This is a scientific explanation because it is an example of motions of objects that can and have been observed using the senses." (*PST1, Written*)

In her explanatory ideals, the notions of demonstration and explanation were spontaneously transposed, and the notion of scientific was associated observation. She onsidered the demonstration to be a pedagogical explanation for scientific concepts.

T3: ambivalent identity, ambiguous dualism of contexts.

T3 recognized the possibility to express her own understanding rather than assuming her teaching identity, but she didn't keep the distinction very clear. Many times, the presumed explainee spontaneously became students. Also the target of her explanation oscillated between the phenomenon and its associated concepts. Her response included elements of inquiry, discovery, pedagogical explanation, mechanistic explanation, theoretical of scientific concepts, and remembered results of their application. But no logical formalism or mathematical deductions were developed.

T1, T2: two possible roles: Teacher or Learner

T1 and T2, made a clear distinction between the use of their subject matter knowledge for teaching and its use in other contexts. They tried to deal with their own content knowledge as asked for this investigation. Considering the experimental observations as the explanandum, they engaged in developing a mathematical prediction. They didn't include the use of the demonstration in teaching. Both of them focused on developing mathematical predictions of the phenomenon.

R1, R2, R3: too many possibilities.

These researchers' idea of scientific explanation also implied a theoretical derivation of the phenomenon, but they remarked that this could be done at different levels of complexity. Given information about the explainee, the context, and the resources, R1 and R2 eventually settled for a reasonable amount of work with college level physics, but R3 appeared to ignore the possibility of different explainees or contexts and focused on alternative frameworks for inquiry.

Part 1: Summary and Discussion

Most of the respondents shared the notion included in the D-N model that explaining a physical phenomenon implies making attempts to derive it from the applicable laws of physics to a particular case. Although they performed this task at different levels of sophistication (as shown in the following section), they appeared to have similar goals and a shared meaning for the idea of scientific explanation. This meaning does not include the teaching of new concepts to the explainee. On the contrary, it involves the selection and application of concepts for which the explainer and the explainee have a common understanding at least in the problem solving frame. However, PST1 and T3 tended to situate the explanation in a teaching context. They viewed the apparatus essentially as a demonstration device for scientific concepts. In other words, concepts became the target of pedagogical explanations, in this case, gravity, momentum, energy, conservation laws, and Newton's laws. This finding was out of the range of the expected types of explanations. Implicit contextual variables needed to be considered regarding the meaning each participant had for "scientific explanation". These variables include the individuals' assumptions regarding the explainer, the explanandum, and the explainee. When these variables are examined, a diversity of assumptions regarding the presumed setting and the perceived purpose of the explanation can be made. Findings from this study suggest that each individual holds a different combination of content and pedagogical knowledge, at least in the knowledge domains invoked by the Newton's Cradle demonstration. It also suggests that these combinations are modified by the amount expertise in the in the domain of physics and affect the individuals' explanatory ideals. The question raises to which extent pedagogical knowledge and content knowledge are distinct for each individual.

Table 2 shows how content knowledge and pedagogical knowledge would be related in each of the extreme types defined in the analysis.

	XTeacher (XTe)	XLearner (XLe)	XResearcher (XRe)
Organization of **content and pedagogical** knowledge	**No distinction.** Subject matter knowledge is restructured or dissolved in teaching knowledge.	**Essentially content.** Subject matter knowledge is in construction.	**Fluid organization.** Subject matter is reshaped according to the settings and goals.

Table 2: Characteristics of content knowledge and pedagogical knowledge in each extreme ID

From this point of view, most of the participants could be classified as close to XLe or close to XRe. They consciously made a distinction and focused on applying their content knowledge and communicating it to a college level explainee. However, PST1 and T3 appeared to be closer to the XTe type. This raised methodological questions in proceeding with the study, regarding the sampling, as well as the possibility to investigate their subject matter knowledge without dealing with teaching contexts. Thus, the subsequent analysis focused on the XLe and the XRe groups.

FINDINGS PART 2. USING PHYSICS TO EXPLAIN THE PHENOMENON

Refernce frame for the problem definition, solution, and assessment

Following the D-N model, a baseline explanation was developed in order to analyze explanations that were congruent with the expected type. The investigator's explanation was organized in four areas which served as a reference frame for data analysis: A. How the phenomenon was described (which assumptions were stated, which frameworks were invoked, which ontological entities were involved). B. How data were determined, which scientific models were selected. C. How the solution was developed. D. How the entire argument was assessed.

These four areas of were represented in Figure 5. They include the solution of a conventional (2-body collision) textbook-like problem (areas B and C), preceded by the assumptions made to delineate the problem (area A), and followed by a discussion of the validity of this explanation (area D).

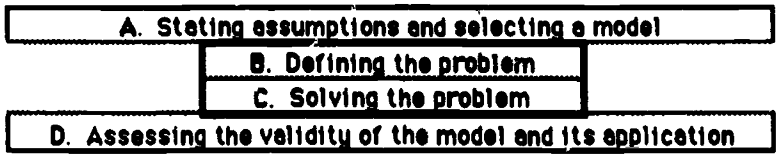
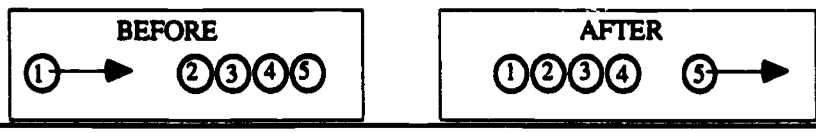


Figure 5: Reference frame for scientific explanation used for data analysis

A. Assumptions: Setting boundaries to the problem.

Explaining that only one sphere takes off corresponds to proving that all but one sphere are at rest after the interaction is completed.



Given the initial state of the system $v_1 = v \quad v_2 = v_3 = v_4 = v_5 = 0$

Prove that the final state should be $v_1 = 0 \quad v_2 = 0 \quad v_3 = 0 \quad v_4 = 0 \quad v_5 = v$

Figure 6: Representing the phenomenon to be explained

Using the conservation laws, we only get two equations for five variables.

$$mv + 0 + 0 + 0 + 0 = mv_1 + mv_2 + mv_3 + mv_4 + mv_5$$

$$\frac{1}{2}mv^2 + 0 + 0 + 0 + 0 = \frac{1}{2}mv_1^2 + \frac{1}{2}mv_2^2 + \frac{1}{2}mv_3^2 + \frac{1}{2}mv_4^2 + \frac{1}{2}mv_5^2$$

Assuming that the materials, shapes, sizes and configuration of the apparatus are such that the interactions between the spheres occur in a sequence of independent two-body collisions of rigid and identical masses in one dimension, the five-body problem represented in Figure 6, becomes a set of two-body problems, all identical to each other as shown in Figure 7

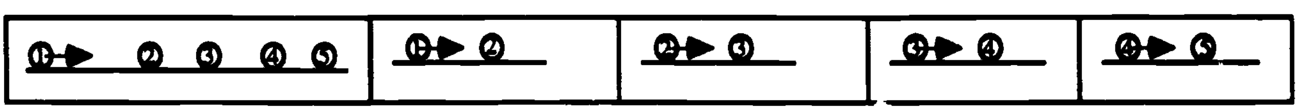


Figure 7: Redefining the problem

B. Defining the Problem: Describing the particular case and the applicable rules

In the presumed case that the interaction between sphere #1 and sphere #2 is completed before sphere #2 hits sphere #3; etc. …, the problem is reduced to the first collision between two spheres.

Given the initial state of the system $v_1 = v$ $v_2 = 0$
Prove that the final state should be $v_1 = 0$ $v_2 = v$

Under the assumption of independent collisions, the case where two-spheres were initially released is similarly reduced to a set of two-body collisions to which the application of conservation laws provide a mathematically well defined problem.

C. Solving the Problem. Making a mathematical prediction

The problem is then to predict the after-collision velocities of identical spheres of mass m by solving two equations. The conservation laws are applied to a system of two masses as shown in Figure 8.

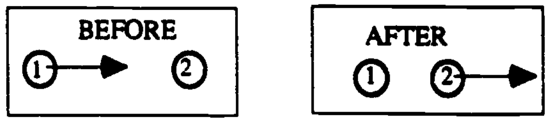


Figure 8: The reduced problem: applying the conservation laws to two spheres at t a time.

$$mv + 0 = mv_1 + mv_2$$

$$\frac{1}{2}mv^2 + 0 = \frac{1}{2}mv_1^2 + \frac{1}{2}mv_2^2$$

Algebraic processing of the equations yields the unique solution:

$$v_1 = 0 \qquad \text{and} \qquad v_2 = v$$

These calculated values for the outcome of the first collision imply that the next two-body collision will have the same initial values as the previous one, thus the same outcome. This corresponds to the observed result that the incident sphere stops and the other one moves forward with about the same velocity.

D. Assessing Validity: Examining the assumptions and Discussing the explanation

The logical structure of this explanation is associated with that of the D-N model. Here, the result of the experiment was logically deducted from the application of scientific laws to the case. However, the reduction of the five-body system to a two-body problem has not been justified.

Analytical procedures: Extending the framework of problem definition, solution, and assessment

Emerging findings required to expand the anticipated range of features attached to explanations. The coding and analysis lead to the addition of two areas to the reference frame. So, a framework of six clusters (shown in Figure 9) was defined in order to account for the diversity of contents in the explanations given by the respondents.

A. Assumptions made about the interaction model were grouped in cluster A. They were related to the notions of *elastic collisions*, *dissipation*, *materials*, *arrangement*, and *contact time*.

B. Statements about the *initial conditions* and the application of conservation *laws* (of momentum and kinetic energy) were grouped in cluster B.

C. The mathematical procedures and logical inferences were grouped in cluster C. They included *solving* the equations and *matching* their solutions with the experiment.

D. Cluster D included the discussion of what information was *undetermined*, the *simplifying assumptions*, *conditions of applicability*, and the possibility to define the problem under different models.

E. In addition to the conservation laws, three kinds of concepts were invoked in association with the collision problem They included *interaction* concepts such as *Action-Reaction*, concepts of angular *motion*, and *transmission concepts*. such as *Force Transfer*. These were grouped in cluster C.

F. Cluster F includes concepts and entities from other frameworks than mechanics of rigid bodies. It completes the discussion on validity by suggesting alternative frameworks including models for *many-body interactions*, *compressional waves*, and *shock waves*..

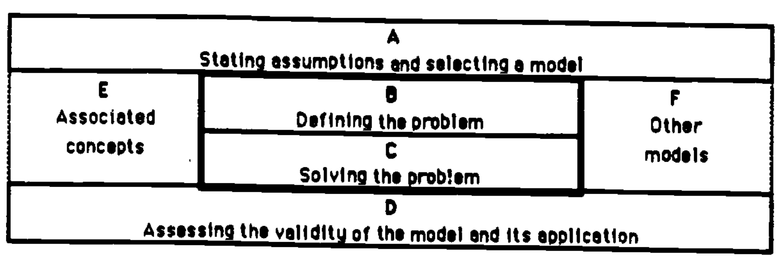


Figure 9: The six clusters representing the diversity of models, concepts and strategies in the explanations

Emerging trends: Overview

Representations of individual responses were compiled on one clusters grid. The teachers' and the researchers' pictures on this grid overlap in the areas of problem categorization and problem solving (clusters B and C). However, it appears that teachers responses included a larger number of associated concepts and fewer considerations regarding the applicability of the model and alternative descriptions of the phenomenon. Although all responses included statements about simplifying assumptions, each group emphasized different issues in this area.

	T1, T2, T3	T1, T2	T2 R2	T1 R2
T2, T3	T2, T3	T1, T3 R1, R2	T1, T3 R1, R2	R2, R3
	T2, T3 R2	T1, T2, T3 R1, R2, R3	T1, T2, T3 R1, R2, R3	R3
T3	T2, /T3	T1, T2 R1, R2	T1, T2 R1, R2	R3
T2, T3	T2, /T3	R1	T1, T2, T3 R1, R2	R3
T3	R1, R2, R3	T1, T2, T3 R1, R2, R3	R1, R2, R3	R1, R2, R3

Figure 10: Cumulative picture of three teachers' and three researchers' responses in clusters

The responses could be described on a continuous scale of complexity considering multiple possibilities for the problem definition, and the assessment of each claim. These levels of complexity seem to be related to the extent to which knowledge from the four frames of understanding was integrated or segregated in the individual's conception. To what extent declarative knowledge was distinct from procedural and situational knowledge seemed also to parallel these levels of complexity.

Researchers' Explanations

Although R1 and R2's explanations included the conventionally expected response, the solution of the two-body problem was presented in their response as part of a more sophisticated set of considerations. They explicitly treated the case as a sequence of independent two-body collisions and solved the predicting equations. In addition, they discussed the delineation of the problem in terms of constraints and unknowns, specifying that the two conservation laws provided two equations for two unknowns, i.e. a well defined problem for a two-body interaction. Finally, they examined the adequacy of the model and its limitations. In R1's, R2's and R3's responses, the 2-bdy model was seen as distillation of multiple features of the phenomenon, after choosing which of them not to consider, but alternatives were mentioned: multiple levels of investigation were possible by making different sets of assumptions. They specified that the assumptions about independent two-body elastic collisions had not been justified, and that this model was selected only for practical reasons. R3 even went to the extreme of not solving the two-body problem since it was not really adequate for this case.

R1's Explanation

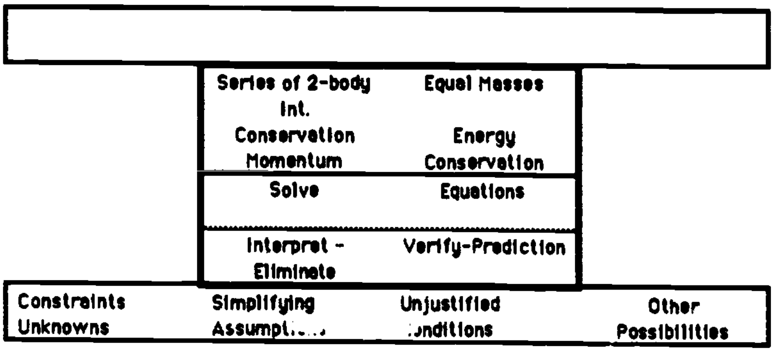


Figure R1: The concepts, approaches, procedures and considerations invoked by R1.

R1 solved the equations of a two-body problem (as shown in the baseline) in detail and he explained how the sequence is repeated until the last sphere takes off. But he specified that the assumption of independent collisions had not been justified and discussed some of the uncertainties associated with this simplified description of the phenomenon. He emphasized the need to question our knowledge and recognize its boundaries. R1 insisted that this is important because remembered solutions may not apply to the present problem, maintaining that the process of determining the *data* from the *experiment* is not a unique procedure, because it involves making interpretations and approximations. In this view, it is essential to recognize and specify the uncertainties that pervade the explanation.

> R1. Now in order to explain what happens, I am saying that you don't see what happens. (R1, Interview. #1, p. 9)

The last paragraph in his written answer illustrates the importance of acknowledging the epistemological limits of the claims and processes on which the explanation was based.

> *Why do you consider this to be a scientific explanation?*
>
> The explanation idealizes without careful justification, breaks the process into simple steps not actually shown to be disjoint, and stops content because it gets the right answer. Now that's science! (R1, Written)

R2's Explanation

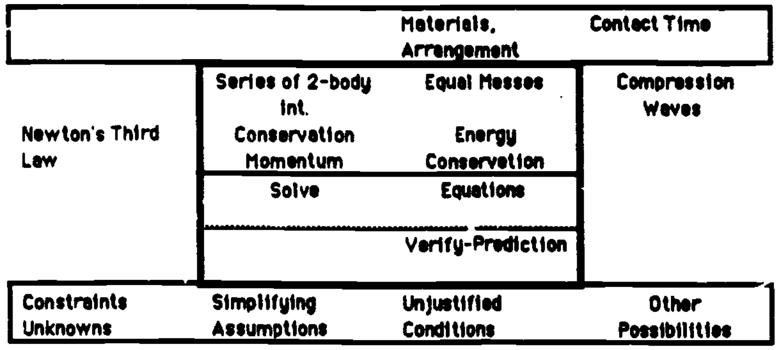


Figure R2: R2's explanation in clusters: This picture of concepts, approaches, procedures and considerations invoked by R2 is also representative of R1's explanation.

R2's response was similar to that of R1's in structure and in substance. After solving the equations of the two-body collision, he emphasized that this case is actually more complex. Like R1, R2 wrote the algebraic procedures for solving the two equations, and predicted mathematically that if each pair of spheres was interacting independently, the incident sphere would stop after transferring all of its motion to the second sphere. Also like R1, R2 considered the apparent match between observations and computational results to be only a necessary condition for the validity of an explanation.

> *4) Why do you consider this to be a scientific explanation?*
>
> This is not a totally satisfying explanation. If the balls are touching each other before the collision, then we must consider ... ... a mechanical wave propagating through the ball. (Written R2)

He emphasized that although the mathematical solution of the two-body problem matches the observed result, the reduction of the case to a solvable problem resulted from pragmatic choices. In his view it is most important to recognize the assumptions and deal with what was not included in the boundaries of this problem.

> R2: We may or may not have to deal with the internal structure of a Newtonian system. We always try to get away without doing it.
>
> I: But once we make an idealization, we need to know what it is we have "thrown away".
>
> R2: That's right, because it will come back and haunt you. *(R2, Interview #2, p. 7)*

R3 as Extrapolation

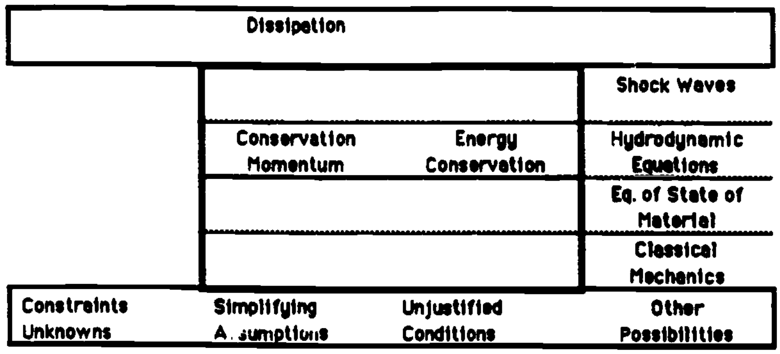


Figure R3: The concepts, approaches, procedures and considerations invoked by R3.

For R3, the purpose of the explanation was also to reduce the question to a solvable problem under conditions that would be specified. He approached the task in terms of *problem* , *treatment*, *equations* , *solutions*, and *assumptions*.. Then, he considered two possible frameworks and what empirical information we don't know. Essentially, he assessed the possibilities of finding a unique solution by examining the degrees of freedom and the application of governing principles.

> The two requirements of momentum and energy conservation, which are expressed in two equations, are not sufficient to determine a unique solution to the system under consideration that has five objects. (R3, Written)

However, R3 chose not to proceed with the conventional solution. Instead, he emphasized the lack of justification for fitting the model of distinct two-body collisions of rigid spheres, pointed to the lack of information necessary for the application of more complex models, and stressed the inadequacy of simplifying assumptions.

> I noticed that the simplistic treatment of classical Mechanics is not sufficient here, and we must make additional assumptions. Then I tried to explain to myself what was really going on, and I concluded that this was a problem of waves (shock waves) propagation in the material. (R3, Written)

In Summary (for the Re's)

Both R1 and R2 developed the conventionally expected response and solved the predicting equations. They explicitly treated the case as independent two-body collisions, applied the two conservation laws, stressing that they defined two equations for two unknowns. In addition, they emphasized issues related to the delineation of the problem and with limitations of that solution, essentially in terms of (a) constraints and unknowns and (b) adequacy of the model.

All three researchers operated essentially from the inquiry frame, challenging the boundaries of knowledge and considering alternative paradigms. They stressed the epistemological considerations and rationales involved in the selection of a theoretical model, questioning the limits of its applicability to the physical situation. R3 did so to such extent that he considered the assumption of independent two-body collisions to be so inadequate that he chose not to develop the solution it offered. R1 and R2 defined and solved the two-body problem with all the mathematical details. But they presented this part of their response only as one of alternatives scientific models to which this case could have been reduced, depending on the level of sophistication and satisfaction desired.

Teachers' Explanations

While researchers operated essentially from the inquiry frame, challenging the boundaries of knowledge and stressing epistemological issues, teachers' explanations proceeded essentially from the problem solving frame, under a single paradigm of elastic collisions.

T1's Explanation

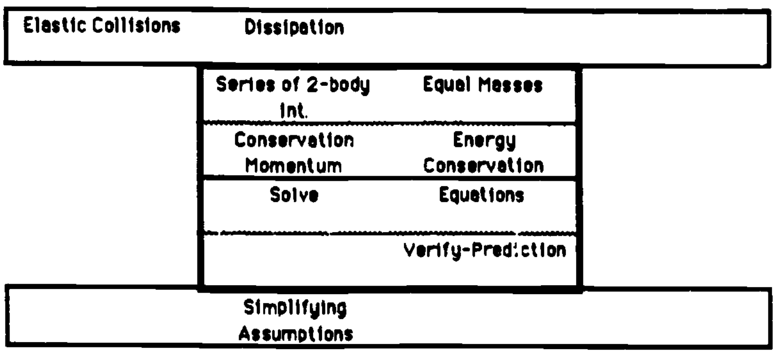


Figure T1: The concepts, approaches, procedures and considerations invoked by T1.

T1's idea of a scientific explanation was also to reduce the phenomenon to a known type of problem and to show, by solving the problem, that the observations were derivable from the laws of nature. She chose to deal with the phenomenon in terms of elastic collisions between, but she specified that it was not completely adequate, because some kinetic energy was lost in each interaction and the motion ultimately died. So she specified that her explanation applied to an idealized system where energy would be perfectly conserved. Although she described the events as a sequence of two-body collisions, the application of the conservation laws was inadequate and led to writing improper equations. T3 experienced difficulties identifying meaningful variables in this case. She needed to define the system to which the conservation laws applied, and to determine data and to chose the unknowns for the problem. The responses indicated that notions associated with transmission concepts and conservation concepts were not distinct. T1 was perfectly comfortable manipulating algebraic equations, but the data and the unknown variables were not adequately defined. How exactly does a conservation law apply? to which entities? This is where most of the confusion occurred. While struggling with the problem, T1 became aware that it was different from the textbook problems she usually teaches. Those ask unambiguous questions, with well defined data, designed to fit the rules in a well specified way. Here, neither the data nor the unknowns were named in the question. She explained that she was familiar with problems of type she usually teaches which she solved by following well defined procedures:

> T1. We were given the two masses that are colliding, and the initial velocities, and we are given whether it's an elastic collision or not, then whether we could apply both formulas, conservation of kinetic energy and conservation of momentum, or may be we can only apply one, -- conservation of momentum -- and ... uuh ... and we would solve them. ... ... We would plug in the values and we would come out with this. And so we would come out with three types of collisions: either perfectly elastic, or perfectly inelastic, or a middle grade, where it would not actually stick together. So, this is the extent of my background about collisions, OK? *(T1, Interview)*

Finally, in order to deal wiht the inconsistencies, T1 reflected upon her knowledge of elastic collisions. She gave up on the mathematics and moved back to an inquiry mode where she questioned the meaning of collisions in terms of contact time and she concluded that this experiment was more complex than it initially appeared to be.

T2's Explanation

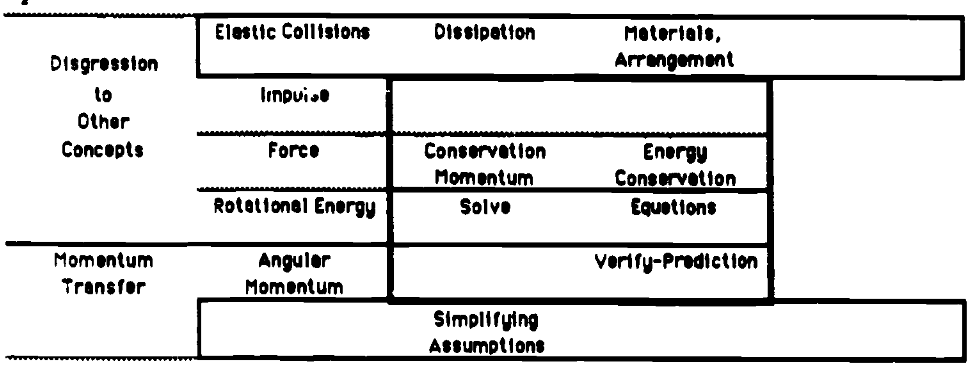


Figure T2: The concepts, approaches, procedures and considerations invoked by T2.

T2's approach to the problem definition led to similar difficulties to those found in T1's response, but he applied different strategies to resolve the contradictions. T2's strategy was to apply more mathematical and theoretical procedures, and deal with diferent variables. He wrote equations of the conservation laws based on linear motion, then, he tested his solutions against conservation laws based on angular motion. The proliferation of computing procedures was characteristic of the *ritual concepts* defined in Perkins and Simmons (1988). Also, his choice of variables was such that the system which he submitted to the conservation laws seemed to be made of a flexible amount of mass or a variable number of objects. In this approach, the question to "which objects are interacting?" or "which system is submitted to these conservation laws?" was not addressed; or perhaps the answer to it was considered to be a variable. This appeared to be a case of Gordian Knot defined in Perkins and Simmons (1988).

T2's primary concern for the validity of the solution was *internal consistency*, as indicaed by the proliferation of logically equivalent arguments and symbolic systems of representations.

I. Why did you decide to also use angular momentum?

T2 I was looking for other ways to test my explanation . So I, to verify it, that if it was consistent, if it was a logical explanation, I must, not matter what variables I start with, I should come out with the same result. *(T2, Interview. #2, page 3, lines 103-107)*

T3 as extrapolation

Disgression to Other Concepts	Elastic Collisions		
	Impulse	Series of 2-body Int.	Equal Masses
	Newton's Third L.W	Conservation Momentum	Energy Conservation
Velocity Exchange	Forces		
Momentum Transfer	System		Prediction
Energy Transfer		Simplifying Assumptions	

Figure T3: The concepts. approaches, procedures and considerations invoked by T3.

T3 invoked a number of concepts associated with the demonstration. The structure of her response was not so clear as the previous ones. It included verbal statements of Newton's third law in terms of impulse, as well as elements of causality and mathematical ratios. But there was no deductive or inductive argument. The relationship between descriptive statements and theoretical claims wasn't clear either.

T3's explanatory ideal was not clearly identified with the D-N model, but didn't exclude it either.. Likewise, the systems and objects to which the conservation laws would apply were not clearly defined. No equations were written.

> I. So this is A, B, [labeling the balls A-E] Which of them are involved in the collisions we are discussing?
>
> T3 Well actually they all are. But the first reaction is between these two, and that is passed on so that the last one goes...
>
> I. So is it like saying that at one point in time [*drawing box around balls B and C*] this is one system, and brief time later [*drawing box around balls C and D*] this is another system?
>
> T3. Yeah, sort of.
>
> I. Now, ... what basically have we explained?
>
> T3. Well, we have explained the interaction between the balls, why one moves off or two moves off and what principles are we talking about here. We are talking about how energy and momentum and force applies in this system and so forth. (*T3, Interview #1*)

In Summary (for the Te's)

Teachers proceeded with a single paradigm and demonstrated a lesser concern for the validation of their claims regarding the selection of the model, its application to the case, and how the initial conditions were determined. These participants specified assumptions or rationale for their claims only in the framework of energy conservation, but not at the level of entities and frameworks. T3 only discussed equations but didn't write or solve any of them. T1 and T2 focused on mathematical equations which they proceeded to solve in order to predict the observed experience. However, their performance resided primarily in algorithmic procedures associated witt the problem solving frame, including some of the *ritual concepts patterns* commonly attributed to novices in expert-novice studies. They engaged in solving equations without being clear about the objects and entities to which they applied. They proceeded computing without specifying the relevant variables, examining the constraints or properly defining the unknowns.

SUMMARY OF FINDINGS

Certain teachers seem to spontaneously situate science related tasks in science teaching contexts. When they do so, the presumed situation appears to be a function of their actual teaching of the topic, goals, classes, students, grade levels. But, for the most part, high school teachers and researchers approached the explanation task according to conventions associated with the D-N model. All the respondents focused on the interactions between the spheres and related the phenomenon to the concepts of energy and momentum. However the arguments proposed as explanations differed in depth and in complexity. Results suggest that the differences in performances were related to: (a) the perceived purpose of the explanation; (b) the number of paradigms invoked for possible ways to describe the events; (c) the specification of assumptions underlying facts or data statements; (d) the examination of assumptions made to determine initial conditions; (e) the choice of variables and unknowns; (f) the proper application of scientific concepts (g) the assessment of the entire argument in view of the acceptability of the underlying assumptions.

Researchers emphasized the epistemic dimensions of their performance more than teachers by: (a) invoking multiple possibilities and paradigms; (b) examining their applicability; (c) assessing their validity before and after performing algorithms. Researchers considered multiple possibilities, invoked multiple paradigms, and assessed the validity of their claims throughout their performance. Teachers proceeded as though there was a single problem associated with the question and a single correct answer. Their activity was essentially situated in the content frame and the problem solving frame, with occasional reference to the other two frames. Their claims, procedures, and strategies could be easily classified in one of the four frames. Although researcher's activity seemed to be inquiry and problem centered, it would be more difficult to classify, since their claims and strategies applied knowledge and challenged its limits simultaneously. This is interpreted as an indication of more integrated knowledge from each of the four frames.

	XTeacher (XTe)	XLearner (XLe)	XResearcher (XRe)
Criteria for explanation: What makes the proposed explanation a scientific and satisfactory one?	Scientific concepts are related to experiments. Students' understanding of concepts is developed through observable demonstrations.	The theoretical prediction matches experimental observations	The theoretical prediction matches observations is only one requirement. A better model would be too complex to handle, but the simple model is actually inadequate.
Locus of emphasis of explanatory ideals	Students' understanding and motivation	Correct solution	Multiple paradigms, model adequacy
Emphasis in the frames of understanding	Subject matter situated in the content frame.	Activity focused in the problem solving frame	Focus on the inquiry frame

Figure 11: Characteristics of scientific explanation according to each extreme ID: Explanatory ideals and focus on frames of understanding

Given the limitations of this study, it is recommended that further research be conducted to support or refute the results about the characteristic performance of researchers and teachers in this case, and to assess their replicability in other areas of physics or with researchers and teachers in other sciences. Nevertheless, these findings suggest a number of conclusions and raise new questions for future research and practice in science education.

DISCUSSION

Scientific explanations of directly observed physical events make powerful tools for probing scientific conceptions from an integrated point of view on understanding. This integrated perspective also implies a revision of the traditional boundaries between conception research and problem solving research. A broader view of the field of problem solving is needed. Recent studies seem to exert this trend to delete the demarcation between problem solving research and deep understanding. (Mestre, 1994; Touger et al., 1994; Mestre et al., 1993). Although the DOE tasks and other methods for probing understanding (White & Gunstone 1992) are based on this assumption, they have been primarily applied either to explore students' naive ideas or to compare experts' and novices' knowledge structures. Their application should be expanded to investigate how individuals perform qualitative analysis of real cases.

Problem definition is one neglected part of science education. The phase of qualitative analysis of a particular phenomenon provides more opportunities to discuss the tentative nature of science than general claims about the refutability of theories do. The qualitative components of scientific inquiry need to be addressed in science education research and in instruction. The authors contend that a shift from algorithmic focused activities aimed at learning how one theory works in already defined cases, to deeper qualitative analysis activities (e.g., multiple descriptions of messy observations) would promote understanding of the gaps between cognition in scientific and everyday domains described by Reif & Larkin (1991). This has implications for the interpretation of test results in conceptions research, for the definition of goals in the (intended) curriculum, for assessment methods and for instruction. Although it is the most difficult to learn, the phase where an observational situation is distillate and reduced to a scientific description of idealized objects needs to emphasized in science learning.

"Scientists strive to make sense of observations of phenomena by inventing explanations for them that use, or are consistent with, currently accepted scientific principles." (Science for All Americans, 1990, p.7). Is the generation of scientific explanations a learning goal of school science? If so, what is a scientific explanation? Philosophers of science deal with the question, but how relevant are their models for practicing scientists? for teachers? Teachers and scientists seem "to do scientific explanations" (though in different ways) rather than talk about them. There is a need to research those particular explanatory ideals which are appropriate for school science to incorporate.

In conclusion, it is suggested that research in science and mathematics education could benefit from an integrated perspective by following Viennot's (1985) recommendations of consolidating the fields of problem solving and conceptual understanding as they are two facets of the same thing and Stewart & Hafner's (1991) proposition to extend the conception of "problem" in problem solving research.

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