The Questions We Ask and Why: Methodological Orientation in Physics Education Research

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Research methodology is discussed using a simple model of students' knowledge. I argue that the nature of data obtained is closely linked to the type of knowledge being probed.

Objectives of Physics Education Research

The research methodology one employs will necessarily depend on one's particular objectives. Our group's objective is to find ways to help students learn physics more effectively and efficiently, to understand concepts more deeply. To do this we seek to understand the process by which students develop their physics knowledge, and what difficulties they encounter along the way.

A Model for Students' Knowledge Structure

To model students' knowledge, Redish uses the analogy of an archery target [1]. The central black bull's-eye represents what the students know well. It contains a tightly linked, hierarchically structured network of concepts understood in depth. When problems related to knowledge in that region are posed to the students, they answer rapidly, confidently, consistently, and correctly, independent of context or representational mode.

The gray circle surrounding the bull's-eye represents what students understand partially and imperfectly. Some concepts are understood well and some not so well; some firmly held beliefs in this region are inconsistent with physical reality. Some links between concepts are strong, but most are weak, absent, or miswired from the standpoint of an expert's knowledge. Knowledge in this region is dynamic and still in the process of development. When questions from this region are put to students they may answer correctly in some contexts, yet incorrectly or incompletely in others.

The outer white region represents what students don't know at all. It contains disconnected fragments of concepts, poorly understood terms and equations, and few or no links relating one fragment to another. Questions from this region yield responses that are mostly noise: highly context-dependent, inconsistent and unreliable, with deeply flawed or totally incorrect reasoning.

Redish, following Vygotsky – who called the gray region the "zone of proximal development" – says that teaching is most effective when targeted at concepts in the gray. ("The zone of proximal development defines those functions that have not yet matured but are in the process of maturation, functions that will mature tomorrow but are currently in an embryonic state [2].") This region is analogous to a substance near a phase transition: a few key concepts and a handful of crucial links can catalyze substantial leaps in student understanding. Conversely, in the bull's-eye region one is merely refining a well-established body of knowledge, while instruction targeted at the white region yields only infrequent and poorly retained gains, lacking stability and durability.

Probing Students' Knowledge

When we administer diagnostics or carry out interviews in which students' bull's-eye regions are probed, we get consistent, reliable, and rather uninteresting results. When we probe understanding in the white region we get inconsistent, context-dependent responses, also uninteresting from a research or teaching standpoint. In contrast, when we probe the gray area, we tend to get rich, diverse, and potentially interesting and useful data.

Sometimes we find relatively stable, internally consistent conceptual islands which may, or may not, be consistent with physicists' knowledge. These islands are likely to have flawed or broken links to the bull's-eye region. When persistent patterns with well-defined characteristics are found, we identify and analyze them. By necessity, we are probing students' responsiveness to minimal guidance, since even asking a question is a form of guidance. In physics terminology we are trying to determine the student's "response function."

We attempt to map a student's knowledge structure in the gray region, and then amalgamate a set of such individual mappings into an ensemble average. We determine the population *average* of things such as typical reasoning patterns, stability of links, responsiveness to probes, etc. We also gauge the magnitude of the natural "line width" to the distributions, that is, the spread around the mean value of the measured parameters [1].

Applying the Model: Sample Research Design

Our group has recently investigated student learning in thermodynamics. A short written diagnostic was administered to several hundred students in three separate offerings of the calculus-based general physics course, and 32 students from a fourth offering of the course were interviewed.

Analysis of the written responses had indicated several surprising results, including a widely prevalent belief that heat and work behaved as state functions, and a very weak understanding of the first law of thermodynamics [3]. The recently published paper by Loverude, Kautz, and Heron [4] had documented very similar difficulties. These results guided our objectives for the interviews; to focus on "gray region" knowledge:

- pose elementary ***baseline questions*** to determine "lower" bounds on understanding;
- use a pictorial representation of a cyclic process to present ***diverse real-world contexts*** in order to probe students' ideas in depth throughout the gray region;
- gauge resilience and ***stability of students' concepts*** upon minimal probing;
- identify key ***learning difficulties***, and gauge their approximate prevalence.

By contrast, there were several alternative research objectives on which we did *not* focus:

- exactly how students had acquired their knowledge *[would be a* ***very*** *difficult task*];
- students' attitudes towards learning *[separate investigation; not our primary interest]*

Although these are limitations on the completeness of our picture of students' thinking, any investigation must be constrained in *some* manner.

Learning Difficulties, Not Alternative Theories

Even alternative conceptions that are clearly and confidently expressed are unlikely to be defended with the strength of a full-blown "theory." Different contexts or representations, or questions using related concepts, may trigger dormant links and influence students to reconsider their reasoning.

For example, in the thermodynamics interviews a lengthy description of a cyclic process was given, with diagrams portraying varying positions of a piston as a volume of ideal gas was alternately expanded and compressed back to its original state. Students were asked this question:

> Consider ***<u>the entire process</u>*** from time *A* to time *D*. Is the net work done *by* the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero?

A *P-V* diagram of the process referred to in the question (*not* shown to the students) is given in Fig. 1. The magnitude of the net work done by the system is represented by the enclosed area, and since the path is traversed counterclockwise the net work done is negative.

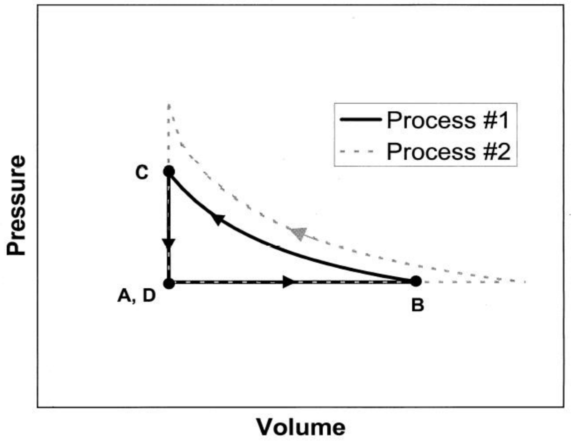

Figure 1. A *P-V* diagram (not shown to students) of the process (Process #1) discussed during interviews.

Most students (over two thirds) quickly and confidently answered that the net work done would be equal to zero. Their explanations expressed just a few common themes, typified by these two:

> "The net work done by the gas…I put equal to zero. I was measuring work as the force over a certain distance, and if your piston is back to your original spot you had a positive work, and you had a negative work. And if you all measured it from the same starting point, you're back to the original point with the same thing. So, you're equal to zero. There *was* work done by the gas on the

> environment, but the *total* work over the entire process is equal to zero."
>
> "I think the net work is zero, because no change in volume…Because work is equal to the integral of $P\Delta V$…and $\Delta V = 0$."

Variations of these arguments were readily volunteered and persistently defended by most of the students. However, 17% of those who initially answered "zero" changed their response after they were asked to draw a *P-V* diagram of the process. Some changed to "greater than zero," and some to the correct response. For these students, drawing the diagram triggered a recollection of the relationship between work done and area under the curve. Their original belief – despite being confidently expressed and defended with a plausible physical argument – was not so stable as to resist a counter-argument spontaneously arising from the students themselves with only a minimal external influence. Thus we found that an apparently strong student conception was at least somewhat unstable when confronted with alternative reasoning.

Although this zero-net-work idea reflects a serious misunderstanding of work in a thermodynamic context, there is no basis for ascribing to it attributes of a full-blown alternative theory. There is no reason to think that students had this conception pre-formulated in any consciously articulated form before they were interviewed. They seemed to be offering explanations that had been worked out on the spot, although most of them obtained the same answer and defended it with similar reasoning. However, their explanations lacked the depth that would be expected from a carefully thought-out physical model.

The precise origin of this student idea – how it abruptly crystallized based on previous instruction and experience – is an open question. It is based to some extent on the common-sense notion that properties of a system returned to its original state must have undergone no net change. However, this line of reasoning also includes specific physical arguments based on students' prior knowledge of physics, including overgeneralizations of both net mechanical work done by conservative forces, and of net changes in state functions during a cyclic process. Those arguments would need to be addressed before students could thoroughly resolve their understanding of these concepts. It is quite possible that this conception, however lacking in the attributes of a full-blown alternative theory, may be quite resistant to instruction.

Investigating Stability of a Learning Difficulty

Through research I try to map out conceptions related to learning difficulties, and to understand what systems or situations elicit them with greatest consistency. Some of these conceptions may be pre-existing in students' minds before their first physics class, but more often they are only vaguely and incompletely expressed until encountered in an instructional setting. There, however, one often finds that they arise with monotonous regularity. An example is students' idea that heat is or behaves as a state function.

We asked students to compare the heat absorbed by the same system in two different processes represented on a *P-V* diagram, both processes sharing the same initial and final states. It was clear from the diagram that the work done was different in the two processes, and so the heat absorbed also had to be different [3]. However, 39% of the students asserted that the heat absorbed by the system would be equal for both processes. Many offered explicit arguments regarding the path-independence of heat, for example: "I believe that heat transfer is like energy in the fact that it is a state function and doesn't matter the path since they end at the same point," "they both end up at the same PV value so…they both have the same Q or heat transfer." Students offered similar arguments to explain – in response to an interview question – why they believed a system undergoing a cyclic process would receive zero total heat transfer. Thus the belief that heat is or behaves as a state function proved sufficiently persuasive that students' responses in two very different contexts were extremely consistent with each other.

A remarkable aspect of our findings was the popularity of *explicit* statements to the effect that heat was "a state function," "doesn't depend on path," or "depends only on initial and final states." Well over 100 students volunteered statements of this type (either in written responses or during interviews), notwithstanding the virtual certainty that they had never read them in any textbook nor heard them from any instructor [5]. They were synthesized by students on their own, and with startling regularity.

It seems that students have some useful intuitions regarding state functions that they improperly generalize (perhaps unconsciously) to the cases of both heat and work. It would be worthwhile to investigate in more detail just how and why this overgeneralization occurs during the instructional process. However, there is great value simply in knowing that it does tend to occur, in knowing the approximate frequency of its occurrence in a given population, and in knowing the form that students' explanations tend to follow.

Interpretation of Students' Reasoning

When we report the results of research, we do not confine ourselves to a bare statistical summary of the data. We offer qualitative assessments based on an overview of all data sources. In particular, we must determine how *consistent* are the various assessments of student thinking. Are the results qualitatively and quantitatively in agreement with each other? Do students offer the same or similar answers when repeatedly probed with related questions? How confident are they in their responses?

Do students offer numerous lines of unproductive reasoning, or do they gravitate toward just one or two? Are there common themes in students' thinking that are not directly reflected in the tabulated data, or in the selected quotations? Do the data and quotations as presented fairly represent the stability and consistency of students' thinking? I believe that researchers should make clear their answers to these questions based on an overall assessment of their data.

Conclusion

The fundamental challenge of research into student understanding is that we are investigating a moving target. Students are always learning, and their mental states are always undergoing change. It is precisely these *changes* – in response to instructional interventions – that are our primary interest. One might well find that two students, whose *instantaneous* mental states (and ability to answer questions) appear to be identical, are actually following very different learning trajectories, with different learning rates.

All assessments – particularly interviews – probe students' thinking not at a single moment, but over a period of time. Students often alter their initial responses under the most minimal probing. The dynamic nature of any assessment raises profound issues of how to view the student's knowledge at one moment in time from the perspective of the learning trajectory (rate and direction) along which they are moving.

Recognition of the fluid nature of assessment has motivated development of the field of *Dynamic Assessment*, documented in many books and journal articles over the past two decades [6]. Practitioners of Dynamic Assessment – explicitly motivated by Vygotskian thinking – have developed assessment protocols that gauge student responsiveness to short-term instructional interventions. These methodologies hold promise for application within physics education research.

The underlying theme of this methodology is that we are probing student thinking that is truly in a state of flux and development, such that conceptual understanding is constantly undergoing evolution and restructuring. The aim of research is not to portray a misleading picture of firmly rooted student concepts, but to provide a snapshot of the interplay and evolution of student thinking – to gauge which aspects are more clearly defined and persistent, and which are relatively flexible and fluid. The more accurately and thoroughly we accomplish that, the better we will be able to develop improved curricula and instructional methods.

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