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So, what is momentum?
One Teacher's Attempt to Understand Student Knowledge Construction in Physics

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INTRODUCTION

This paper describes results from a project which investigated student knowledge construction in secondary school physics over a period of four months. The research was designed to examine the relationship between teacher instruction and student learning in a secondary school physics classroom. Interpretation of data collected was made using a theoretical foundation of constructivism as described by von Glasersfeld (1995, 1988 and 1984) and integrated with alternative conception literature in science education (see for example, Wandersee, Mintzes & Novak, 1994). These two areas in the science education literature provided a lens through which to interpret the data.

My personal experience in science education includes an extensive period as a classroom teacher in secondary schools teaching junior science, and senior chemistry and physics. My teacher education occurred in the 1970s and was steeped in "discovery" and "inquiry" methods of science teaching. Over the years I had become disenchanted with the description of student learning provided by discovery and inquiry learning theories. Student learning experiences in my classrooms never seemed to occur in quite the manner described by research of that era. When students were directly involved in activities they were enthusiastic about science and learning, but they did not seem to learn the concepts in the way that I planned. This research program was designed to explore student learning in science and the questions that it posed to me.

Piaget's stage theory of cognitive development seemed to explain some student difficulties in my classes. The idea of developmental stages seemed to describe classroom events more accurately than other theoretical explanations; for example, cognitive development seemed to explain why density was a difficult topic to teach to students in grade nine. Although some applications of Piaget's work to classroom issues were proposed, most studies seemed to deal with statistics concerning numbers of students at each developmental stage, or how students could be accelerated through the stages. These results were of little use to classroom teachers mainly because students at all levels of development are present in our classrooms; and, even if each student could be categorized, teachers had to deal with all students in the same classroom.

Alternative construction literature which first appeared in the 1970s provided a better description of student learning as I experienced it in my classrooms. My students developed conceptions that I did not intend, and did not replace their prior conceptions with new ones I presented. This body of educational research literature seemed to reflect many learning incidents that I had observed while teaching in secondary science classrooms. When combined with constructivism as described by von Glasersfeld, I felt that I had found a body of educational research literature that brought meaning to my classroom experiences, and provided me with a vocabulary allowing me to describe and explain the concerns and problems that appeared when I reflected on my classroom teaching.

THE RESEARCH STUDY

In my research study I taught senior physics to a group on nine students in a Western Canadian city. The research project was centred on these students learning to apply vector mathematics to represent physics concepts and to apply this knowledge in problem solving activities. Each class was videotaped and other data were collected. I was an active participant in the research and could not make field notes as a detached observer. I kept a detailed personal journal of my experiences but entries were made after the classroom sessions.

My experience when teaching students to use vector mathematics in physics has been that most students struggle with these complex concepts, and that I struggled when instructing students about the use of vector mathematics. In the study I taught these students to use vector mathematics in a variety of physics situations (and for some students taught them about vector mathematics for the first time). The content of this paper is an account of the classroom experiences as students struggled to construct the concept of momentum.

INSTRUCTING ABOUT MOMENTUM

Momentum is an example of a physics concept which grade 12 students bring to class in a form that is different from the concept used by physicists. Most students had heard the term *momentum* used in reference to sporting events, or to objects tending to keep moving but these are the usual extent of their knowledge of momentum. Assisting students to reconstruct their knowledge to bring it more in line with that of physicists is a difficult task because their concept of momentum is normally weakly constructed and quite different from the term used in physics.

Deciding when to move on and introduce momentum was not simple because a balance between "covering the physics curriculum" and the level of understanding by students had to be considered. When I introduced momentum, I was under no illusion that my students thoroughly understood the application of vector mathematics to physics problems, but a new topic involving vector representation could be useful to spur their learning. The following conversations illustrate to some extent the students' prior knowledge of momentum at the beginning of the unit.

Tchr[1] - How many of you have heard of impulse and/or momentum?

J - I've heard of momentum.

Tchr - ... What's it about? Do you know?

A - You stop applying force but it (an object) keeps going.

Tchr - ... Oh I see, I hadn't actually thought of it that way.... You stop applying force but it keeps going. I kind of like that idea.

Tchr - What does momentum depend on?

J - Velocity ... Force

Tchr - Momentum is proportional to velocity ... but what else?

J - Mass

Tchr - What else can you tell me about momentum? How would you change it?

J - Add more velocity or more mass to it (object).

Tchr - Yes, we could do that, but supposing you have a fixed object ... say a baseball or something like that, and you want to change it's momentum.

[1] In transcribed sections "Tchr" is myself as teacher. Students are abbreviated to initials of their names.

K - Add a force.

Tchr - OK, add a force. Add a force or apply a force?

T - Apply a force.

Tchr - Sure, apply a force, that's all it is ... apply a force.

Tchr - What other factors?

(long 10 second pause)

J - Whether it's a constant force or something like that. A quick force?

Tchr - A quick force or a constant force. So what really are you saying is the difference between those two?

J - One's partly pushing it and ones pushing it.

Tchr - So what's the difference?

J - One's going to run out.

Tchr - What's going to run out

J - The force.

Tchr - The force is going to run out? The force runs out ... what an interesting idea.

J - Well, it will slow down again.

Tchr - Does it? Why would it slow down?

J - There's friction.

Tchr - What if I'm in outer space? Let's pretend there's no friction and it (object) is in outer space, and you give something a little flick.

J - It will go.

Tchr - It will keep going?

J - Yeah.

Each student came to my physics class with some understanding of the concept. *Momentum* was in everyone's vocabulary but each participant had a different comprehension of the concept. These excerpts left little doubt about the incomplete structure of their knowledge.

Anne's idea was that momentum was the property of an object that keeps it going after the application of a force has stopped. Judy knew that momentum was somehow related to mass and velocity and believed that force was also involved. Her view of increasing momentum by adding "more velocity or more mass" to the object was theoretically correct but did explain how to make those changes. Kevin appeared to understand that an applied force was required to change the velocity of an object.

Judy's idea of different forces was not clearly explained and she was not able to clarify her distinction even with further discussion. Her idea that the force was going to run out was similar to Aristotle's views on force and motion, and consistent with other novice physics students (McCloskey, 1983). Judy was able to see a contradiction in her understanding because she was aware that friction slowed objects but that they will move essentially forever in space because of a lack of any retarding force.

Some concepts, such as momentum and entropy, are used by scientists, but not intuitively identified by students. Momentum was a difficult concept for these students because their everyday experiences had not created a need for its construction. Without identifying a need for momentum they (and most other people) did not abstract the concept from their experiences as physicists have done. Until this class they have operated successfully without understanding momentum. Creating a need for momentum in their experience is not easy for physics teachers. One commonly used activity uses "exploding" momentum carts to explore the conservation of momentum. They performed such an experiment to provide them with personal experiences of momentum.

The participants completed the investigation and discussed the activity and calculations arising from it. They interpreted their results and measurements to illustrate the expected result that momentum was conserved in this experimental situation. This lab activity seemed to have produced the anticipated learning; and, all seemed in order until we discussed the significance of their experimental results.

> Tchr - But what does it show you if it (momentum before and after the spring release) equals 0.
>
> C - They were stopped.
>
> Tchr - No. They didn't stop, they were moving.
>
> C - They're both in motion.
>
> M - They're both moving with the same speed.
>
> Tchr - ... except that is not always true, because if there was a heavier cart it moved slower than a lighter one.
>
> C - It doesn't make sense.

Colleen was confused about the momentum of the two carts totalling zero because they were moving. First, she responded that her experimental result meant the carts were stopped, then a few seconds later changed her response by indicating her results meant the carts were moving. Her view was that moving carts had momentum and was not able to consider the vector nature of momentum or that both carts had to be considered. In spite of her confusion some students intuitively understood the phenomenon investigated in this activity. Colleen knew two carts moved away from each other when the spring was released and their velocities were inversely dependent on their masses; however, she did not understand how the momenta totalled zero. Like Colleen she was unable to understand the significance of the vector nature of momentum either. Even though students could correctly predict the motion of carts with unequal masses, they did not have a comprehensive understanding of momentum.

> C - That doesn't make any sense though, because sometimes the cars had different speeds, so even if they take off in different directions they don't cancel.
>
> Tchr - They weren't going the same speeds.
>
> C - And they weren't going the same velocity.
>
> Tchr - No, they weren't going the same velocities either. Were the masses the same?
>
> C - No.
>
> Tchr - What happened if you had a heavy cart, did it move slow or fast?
>
> C - Slow.
>
> Tchr - Slower ... so you have a big mass times a little velocity. If it (cart) was a lower mass, what was its velocity, higher or lower?
>
> A - Higher

Students had some understanding of conservation of momentum, but they had not developed a functional understanding of the concept or its mathematical model. That students did not really understand momentum became clear during the following conversation.

> K - Well, what exactly is momentum?
>
> C - What is momentum? ... Yeah, how do you define it.
>
> Tchr - Well, you tell me.
>
> C - How can you conserve momentum when things are moving?
>
> Tchr - That's a good question. You tell me, what do you think

momentum is?

C - I thought momentum was something moving.

K - Momentum is ... Is it a force?

Tchr - Then what do we call a force?

K - It's a specific force.

Tchr - Remember in physics we identified ... concepts. We've identified force and we have a pretty good idea of what forces are.

K - It's like an internal force.

Tchr - But it's not like ... a force.

C - It's a force that works off the friction.

Tchr - ... but is it a force?

C - I don't know.

Tchr - But if it were a force ... why don't we call it a force? There's no point in thinking up a new word if it's the same thing. If it were the same thing as force, physicists would just call it *force*.

C - It just doesn't make sense.

Of interest here was the variety of ways in which students tried to construct momentum as a concept. Initially Kevin and Colleen simply requested a definition of the concept which I did not attempt to give because I was quite sure I could not provide the type of definition they were requesting. They wanted a definition or a list of characteristics describing momentum that would allow them to identify it in their experiences. They were not seeking a mathematical formula.

Colleen explained her comprehension of momentum as "something moving." Her version of momentum was consistent with her confusion expressed earlier when she could not understand how total momentum could be zero when the two carts were moving in the previous experiment. Kevin, on the other hand, tried to construct this new concept by relating momentum to his concept of force, arguing first for a "specific force" and later for an "internal force." He did not provide a definition of either term. I suggested to him that if momentum were a force it would have been called a force. Next I explored their understanding of the concept by trying to get them to use the word in the manner consistent with their constructed meaning.

Tchr - How would you use the word (momentum)?

A - Well, you could say, it kept going because it had momentum.

Tchr - OK, it kept going because it had momentum.

J - Is momentum motion, or is momentum like a ... number?

Tchr - What is it?

M - Tell us.

Tchr - But my answer to you is going to be ... a mathematical expression of mass times velocity.

M - But what does that tell you?

Tchr - Exactly, what does that tell you?

This section of discussion was also illuminating. Judy wanted to know if momentum was motion or a number. She was exploring the possibility that her understanding might have been enhanced if she could quantify the concept. If she understood how momentum was measured she thought that she might be able to understand the concept more completely. By this time Marie clearly was frustrated and appealed to me to "tell us" the answer, as if it were a secret that I was keeping. When I explained that the only simple answer that I can give them was in the form of a mathematical formula, she recognized that this type of answer would not have satisfied her needs. I did not know how to answer them directly in the manner that they wanted so I redirected our discussion.

Tchr - Supposing something (an object) were moving towards you on pavement and you have to stop this thing. What is going to determine how far you slide when this thing runs into you?

A - Mass and velocity.

Tchr - Both together, or just one of them?

C - Both.

J - Both.

Tchr - Could you figure out the sliding distance with just the velocity or the mass.

J & C - No.

In this interchange I tried to have them imagine a scenario where they would have to stop some object moving toward them on a sidewalk by standing in front of the object and being pushed backward. Colleen, Anne and Judy all seemed to understand that both mass and velocity of the object were required to determine how far back they would be driven.

Tchr - How would you describe that characteristic ... of mass and velocity?

C - Momentum.

Tchr - OK, so momentum is that sort of ... now you said it's how long it keeps it going ... I might say how much "oomph" there is in it.

J - With the kid coming toward you ... and he has momentum. He has a mass times velocity.

Tchr - Right.

J - So what's the momentum equal to ... is that a big number or a little number?

Tchr - Well, why don't you figure it out?

C - OK, say he's going really fast.

Tchr - How fast? 10 m/s that's pretty fast.

C - Yeah, and he's like a 100 pounds ...

Tchr - 50 kg good?

C - Yeah.

Tchr - OK, so 50 times 10 m/s would be 500

Judy was again trying to explore momentum in terms of the property that a child on the tricycle had as he was coming towards her. She and Colleen wanted a quantifiable way of expressing momentum and came up with 500, but they had not included the units with the number. Including units might have created more understanding, but in this case the units are N•s (Newton•seconds) and students have had little experience with them.

Tchr - ... assuming you were on roller skates and a kid (on a tricycle) comes along and you grab onto him. Right, you hold onto him. What happens to you ... and him?

J - You'd gain some momentum.

Tchr - You'd certainly gain some momentum, you start moving in the direction he's moving in, right? How fast do the two of you go, if you hold on to him?

M - You'd slow down.

Tchr - Why?

M - Because there's more mass.

Tchr - That's right, more mass, smaller velocity.

In this final section I asked them to imagine that they were on roller skates and then pulled along the sidewalk by someone on a bike. Their intuition was correct in this thought-experiment because they predicted that some momentum would be transferred to them and the combination would move slower than a child alone on the tricycle. In spite of understanding a practical situation they were unable to express what was transferred or to describe momentum in a way that was meaningful to them.

This extended conversation was spontaneous and generated in the classroom. My instruction and questions were adapted as I interacted with the students. Scenarios were created as needed, not planned in advance. While teaching I was aware of the participants' struggles to understand momentum and tried to facilitate their knowledge construction. In spite of this awareness only after studying transcripts of this interaction did the range and variety of struggle become apparent. My detailed picture of student learning did not emerge without considerable analysis and interpretation.

REFLECTIONS ON THIS EPISODE

This description of student learning was illuminating in a number of ways. The first was to show how on the surface an instructional strategy appeared to produce learning. Participants had completed a traditional momentum cart activity. Videotape records showed that they performed the activity and understood the procedure that was carried out. As well participants understood what results they expected to get. A post-lab discussion initially showed that they understood the results and could even see applications to other natural phenomena. To that point instruction was routine and seemed to show results that were anticipated from this strategy.

Second, when probed more intensively about momentum, a lack of depth of student understanding was exposed. Students had not constructed this concept with sufficient understanding to be of functional use in physics. Students had exhibited a form of rote learning as a result of this lab activity rather than meaningful learning (Ausubel, Novak & Hanesian, 1978).

A third illumination produced from this conversation concerned the variety of methods students used to construct understanding of momentum. Colleen's concept of momentum involved objects moving, but she became confused when she applied it to her experimental results. She could not resolve her confusion that total momentum was zero when objects were moving. She wanted logical consistency but was unable to achieve it. Kevin wanted a definition of momentum but when one was not forthcoming, he tried to describe momentum in terms of force a concept which he understood. This approach was unsuccessful because momentum is not a force and his terms “internal” and “specific” were not clearly formulated. Judy attempted to build the concept in terms of how momentum was measured. She used this approach because she understood other concepts in terms of the units in which they were measured. Marie wanted me simply to tell them an answer. Her request resulted from frustration but indicated that she thought an understanding of momentum could be directly transmitted to her.

This discussion lasted about twenty minutes and provided several different examples of knowledge construction by students. In addition this discussion provided an evaluation of a laboratory approach to instruction. The surface results indicated that learning had occurred as expected, but a deeper analysis of the conversation showed that learning was superficial and few connections were made to student experiences.

ASSESSING STUDENT UNDERSTANDING OF MOMENTUM

The participants wrote a test to assess their knowledge at the end of the momentum unit. The day following three students and I discussed their work. I began by asking how they went about solving a physics problem. All three indicated they began by isolating the variables in the problem and then looked for an appropriate formula, a process they have been told to follow in many mathematics and science classes. After identifying a formula they substituted the numbers and made calculations. None attempted to identify which physics principles should be applied to a problem, or tried to estimate an answer using visualization. This result is consistent with other reports on problem solving in physics by novices (Maloney, 1994).

One problem on the test involved a cannon recoiling backwards after firing a shell. Marie and Colleen got the correct answer (about two metres) but Anne calculated the answer to be about 32 000 metres. When I pointed out the enormous error in this answer all three readily recognized that 32 000 metres was an unreasonable answer. When asked about her work Anne said that she simply did not think about answers after completing calculations. Marie and Colleen were not surprised at her response because neither of them considered whether an answer was sensible after finishing the calculations.

Another test problem required that they calculate the momentum and kinetic energy of a moving car. All three answered this question correctly but our discussions showed that they had essentially no idea of what properties of the car that they had calculated. They knew the labels, momentum and energy, but none could visualize or comprehend these characteristics of the vehicle. Both quantities are abstract and depend on mass and speed (velocity). Students were not able to describe the difference between the quantities even though they could calculate them and assign units.

This discussion around their work on the test was enlightening. These three students used formulae uncritically in problem solving thinking about the nature of a problem or the underlying physics principles. They did not estimate answers nor evaluate them to see if they were reasonable. These were not the problem-solving skills that I had hoped I was teaching them as they participated in my physics classes. These observations of student approaches to problem solving are similar to several described (see Maloney, 1994).

FINAL DISCUSSIONS WITH STUDENTS ABOUT MOMENTUM

About six weeks after the unit on momentum I asked the students to explore their thinking about momentum by writing about why the concept had been easy or difficult to learn. The following is a sample of their written responses.

> A - The concepts that I found difficult are things that don't have a concrete explanation. For example, there is no constant explanation for momentum. I also have a problem with concepts that are not "hands on".

> D - Momentum was difficult to learn because I get the formula for it mixed up with other formulas for other concepts.

> L - I found momentum difficult to understand and learn because I couldn't develop a picture of what momentum looked like. I couldn't figure out how to apply this to something in real life.

Students expressed their difficulties in various ways. Some were unable to visualize momentum. In other words, they were unable to understand what characteristic was being abstracted from their environment. Dean stated confusion about the formula representing momentum. He was unable to identify a correlation between letters in a formula and the feature in his experiential world that was being represented. The students did not indicate that vector mathematics was a source of difficulty when learning how to represent momentum. Their main concern was they could not recognize momentum in nature.

The following are some verbal responses that individuals used to describe momentum.

T - I don't know. I know what momentum is, if you just use the word *momentum* ... I know what it means, like in a football game or something ... but to use it as a formula and stuff ...

J - Mass times velocity

Tchr - Is there any other way you could describe it?

M - Energy?

Tchr - It's not energy though. It's mass times velocity.

L - It's the way things go, like it's how fast an object will go.

Tchr - But isn't that just speed, if you are talking about how fast something will go?

J - It's how much it will move something else if it hits it. It's the amount of force something has ... like how much ... it's the amount of force it has in it, then the force is created by the mass.

Tchr - OK, then you are thinking of the amount of force in an object.

J - Yeah.

These comments indicated that my instruction had by no means assisted them in constructing complete concepts of momentum. They did not understand momentum in the manner that physicists do. These comments caused considerable reflection about my approach to teaching students about momentum.

CONCLUDING THOUGHTS ABOUT TEACHING MOMENTUM

The majority of secondary school physics students do not understand the process of mathematical representation that is an important part of studying physics. Students treat physics formulae as algebraic expressions to be solved mathematically rather than representations of physics concepts. At times I have fostered this attitude in students by providing algorithms for solving problems and clues in the questions to help students choose the correct pathway to the solution. I had hoped I was providing my students with a better view of this relationship, but the results discussed in this paper are convincing evidence that additional changes in pedagogy are required if meaningful learning is to be facilitated.

Momentum is a complex concept and illustrates the problems faced by secondary school students when learning to represent concepts with mathematical models. First, momentum is abstract because it is not normally identified by students during normal life experiences. Second, momentum has direction dependent characteristics, that is, it is a vector quantity. Third, to represent momentum mathematically vector mathematics are required. These three aspects of momentum provide considerable difficulty for students.

Identifying concepts and relationships between them is not a process that most senior science curricula explore in detail. By the time students take senior science courses it is assumed that they understand this process. My experience and this study show otherwise. To help develop this ability activities need to be created to give students experience in working qualitatively with relationships between concepts. Once they understand the qualitative relationships, students can be taught the process of representing them mathematically. Qualitative experience would be the first step in developing understanding of mathematical representation.

Enhancement of student understanding of mathematical representation cannot be achieved in senior physics classes alone. Students need to explore this process much earlier in their formal education. Science and mathematics curricula could be structured to provide students with assistance in constructing mathematical representations personally. Classroom experiences could be designed in a manner that successful solution is dependent on students developing mathematical representation of concepts under investigation. Potential exists for using computer software to provide simulations of relationships.

It may be possible to introduce some fundamental aspects relating mathematics and science in elementary and middle years science and mathematics curricula. Early introduction would be pedagogically sound because it allows students more opportunities to revisit and reflect on the process of mathematical representation. The use of manipulatives in elementary mathematics classes could help students in understanding mathematical representation because using manipulatives to represent mathematical operations is related to the process of concept representation that we require students to achieve in the secondary sciences.

Not understanding the process of mathematical representation made understanding the use of vector mathematics even more difficult. The participants lacked a perception of any need for vectors or vector mathematics. Students did not have a sense of why they had been taught about vectors in other classes, nor why they were necessary to solve momentum problems. This deficiency was clearly illustrated when students drew vector diagrams to help with adding and subtracting. They did not view these diagrams as aids which showed a resultant vector; rather, they saw the diagrams as a separate problems.

My students' inability to identify direction as a significant characteristic of momentum and other physics concepts was a major concern. I have come to realize that in their lives most situations and problems did not require awareness of direction as is required in physics. Initially I considered that driving a car was a situation that established a need for thinking about direction; however, on reflection I have concluded this was not so. A driver has to choose the correct road, but once chosen, few navigational skills are required to arrive at destinations. Students tended to see direction as relating to the earth and not to concepts in the physics.

This lack of identifying the importance of direction in physics concepts adds to the inability of students to understand vector mathematics. Without identifying direction as a fundamental characteristic of certain quantities, students cannot be expected to see any reason to use vector mathematics; and, vector mathematics will make little sense to them until they are able to understand why direction must be part of some mathematical representations.

Although I have discussed these points individually, any solution will have to take into consideration their interdependent nature. Resolutions of all problems identified by this research can not be made in senior physics classes alone. Most science teachers do not have the arsenal of instructional strategies necessary to create these experiences for students because this type of approach had not been to any extent part of science education programs.

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