Learning about A Level Physics students' understandings of particle physics using concept mapping

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Abstract

This paper describes a small-scale piece of research using concept mapping to elicit A level students' understandings of particle physics. Fifty-nine Year 12 (16- and 17-year-old) students from two London schools participated. The exercise took place during school physics lessons. Students were instructed how to make a concept map and were provided with 24 topic-specific key words. Students' concept maps were analysed by identifying the knowledge propositions they represented, enumerating how many students had made each one, and by identifying errors and potential misconceptions, with reference to the specification they were studying. The only correct statement made by a majority of students in both schools was that annihilation takes place when matter and antimatter collide, although there was evidence that some students were unable to distinguish between annihilation and pair production. A high proportion of students knew of up, down and strange quarks, and that the electron is a lepton. However, some students appeared to have a misconception that everything is made of quarks. Students found it harder to classify tau particles than they did electrons and muons. Where students made incorrect links about muons and tau particles their concept maps suggested that they thought they were mesons or quarks.

Introduction

Particle physics is a particularly interesting topic because it is an active area of physics research. These are exciting times because the ATLAS and CMS projects at the Large Hadron Collider (LHC) reported strong evidence for the discovery of the Higgs boson in 2012 (Aad *et al.*, 2012; Chatrchyan *et al.*, 2012). Confirmation of the existence of the Higgs is important in supporting physicists' current model explaining why some particles have mass (Adams, 1988). The experimental data are a result of a monumental international effort at CERN, with the original ideas conceived in the 1980s, construction approved in 1994, and the 27 km accelerator finally seeing its first particle collisions in 2010, at a cost of some 3 billion Euros for the machine alone (CERN Communication Group, 2009).

Particle physics has been a compulsory part of A Level Physics specifications in England since 2008, although it has been included in some syllabuses since the early 1990s (Swinbank, 1992). The topic builds upon the study of basic atomic theory in Key Stage Three (ages 11-14) and of the structure of the atom in terms of electrons, protons and neutrons in Key Stage Four (ages 14-16) (DfES, 2004.)

There is a considerable body of research on children's understandings of particle theory, where the particles concerned are at the atomic level. Harrison and Treagust (2002) suggest that there are seven widely held misconceptions:

1. Although children may be able to state that matter is made of atoms, they think that the atom is a small piece of the bulk material having the same properties as the material as a whole

2. The idea that there is empty space between the atoms or molecules is not understood; children have a continuous model of matter in which the atoms or molecules are surrounded by some other substance – possibly air

3. The size of atoms is not appreciated – with children thinking that atoms can be seen under the microscope (possibly as a result of having seen images of atoms produced by scanning tunneling microscopes).

4. The continuous, random motion of particles in gases is not well understood.

5. Children don't know the relative spacing of particles in solids, liquids and gases – not appreciating how close together they are in liquids, nor how far apart they are in gases.

6. Children may not appreciate that matter is conserved in phase changes.

7. Children explain the thermal expansion of materials in terms of the particles themselves expanding, rather than in terms of the mean distances between particles increasing.

Little research appears to have looked at children's ideas about the subatomic level, but the findings suggest that children find this difficult too. In a study of 1635 pupils, in Tasmania, looking at knowledge of definitions of science concepts, using multiple choice tests, about 60% of students in grades 9 and 10 (aged 14-16 years) could identify that protons are found in the nucleus and that electrons orbit it (Lynch & Paterson, 1980). The propositions about the substructure of the atom that were being investigated were:

- The electron is 'the negatively charged particle found in an atom'
- The proton is 'the positively charged particle found in an atom'
- The neutron is 'the uncharged particle found in an atom'

The researchers reported that the children's responses suggested that they were confused about the charges on the particles.

In another study, Taber (2012) investigated 15-18 year-olds' understandings of the solar system model of the atom, by carrying out interviews in which the questions focused on the forces acting between particles. He found that knowledge of electrical forces of attraction between the nucleus and the electrons was weak.

Taking these two studies together, perhaps students did not understand how the explanatory idea of forces relates to the structure of the atom, and perhaps this contributed to them finding it difficult to memorise the charges on particular particles. Taber (2012) suggested that teaching of electrostatics could be strengthened to support understanding of the significance of charge.

Before particle physics was introduced into the school physics curriculum, Barlow (1992) predicted that there would be challenges involved in teaching the topic to A Level students. Whilst supportive of the idea of introducing particle physics into the school curriculum in order to engage and motivate students, he expressed concern about whether or not it would be possible to present the material in a way that was not simplistic and superficial. He pointed out the need to have an understanding of quantum mechanics, for example, in order to be able to understand the particle physics topic, and quantum mechanics is not covered until undergraduate level.

Hence I was interested to know more about A Level students' understandings of the topic. At the time of beginning the research, I had only recently moved into a research role from classroom teaching. I became interested in using concept mapping as a tool for two reasons.

Concept maps were first developed as a means of allowing learners to reveal their conceptions of school science topics – the written representations being taken as a proxy for the learner's cognitive structure (Novak & Canas, 2008). White & Gunstone (1992) suggested that concept mapping can be an indicator of the quality of students' learning, and Novak and Gowin (1984) suggested that students' concept maps are useful to teachers because they can show areas that students have learned or not learned, as well as misunderstandings.

I was also concerned about the lack of linking between educational research and teachers' practices. It seemed to me that it would potentially be helpful to teachers if I used a method that would be feasible for teachers to use themselves. This might enable them to reproduce the investigation with their own classes to see whether or not its findings are of relevance to their own teaching.

Hence my question is what does concept mapping tell us about A Level physics students' understandings of the particle physics topic?

Methods

Invitations to participate in the research were sent to six of the partner schools from King's College London's Postgraduate Certificate in Education (PGCE) programme, where A Level Physics was taught, and where I had contacts as a course tutor. Two of these schools participated – two state maintained London schools, including one comprehensive co-educational school (School 1) and one selective boys' school (School 2). Both schools were teaching the Assessment and Qualifications Alliance (AQA) 'Physics A' A Level specification (AQA, 2007), in which particle physics was taught in Year 12. All the students taking Year 12 physics in these schools agreed to take part in the study, which took place towards the end of their AS year – after students had studied the relevant topic. There were 21 students from School 1 and 38 students from School 2. Students took part in the study during one of their timetabled physics lessons – a period of about 90 minutes.

Being aware that if students are more proficient at concept mapping then their maps will be a better representation of their knowledge (McClure *et al.*, 1999), in the lesson I first introduced the students to the process of concept mapping. They were shown two examples of concept maps for a different area of science, with which students should have been familiar from earlier study. They were asked to compare the maps, identifying which one they thought was best, and giving reasons for their decision. They were taught the general features of concept maps (White & Gunstone, 1992): a hierarchical structure with the most general concepts at the top, and the most specific examples at the bottom; the labelling of links between concepts; and that better quality maps include cross-links from one area of the map to another.

Students were then shown a list of key words about the particle physics topic. The key words were chosen by referring to a commonly used A Level Physics textbook (Trevillion, A. & Priddle, G. (Eds), 2001). An initial selection of words was made by choosing the ones that were highlighted in the text. Bearing in mind McClure *et al.*'s (1999) concern about the quality of concept maps being less good if the task is too complex, the list was edited down, by choosing the words I considered most relevant. I then piloted the activity with a group of PGCE physics trainees, and made minor amendments. The final list of key words was as follows:

Annihilation, atom, charm, lepton, baryon, bottom, antiparticle, down, neutrino, hadron, meson, nucleon, matter, muon, proton, quark, strange, tau, particle, up, neutron, electron, top, nucleus

The vast majority of the words are the names types of particles, with ‘matter’ and ‘annihilation’ being the obvious exceptions.

Students were provided with A3 paper and small sticky notes. They were given the following instructions, based on the recommendation of White and Gunstone (1992):

1. Look at the key words and write ones you know on the sticky notes. Leave out any terms you don’t know or which you think are not related to any other term.

2. Put the remaining terms in rank order (or diamond) with the key concept(s) (most general) at the top and the most specific at the bottom

3. Arrange the sticky notes on the sheet of paper in a way that makes sense to you. As far as possible arrange them in a hierarchy with the most general at the top.

4. When you are happy with the arrangement, leave them stuck down, or write them on the paper.

5. Draw lines between the terms you see to be related.

6. Write on the line the nature of the relation between the terms. It can help to put an arrowhead on the line to show the direction of the relation. Examples of linking words: is, is made of, can be, contains, have, are.

7. If you left out any words in step 1, go back and see if you want to add any of them to the map. Remember to include links and to write on the nature of the relation.

8. You may add your own examples.

The activity was carried out independently by each student. Concept maps were collected in at the end of the lesson.

Novak and Gowin (1984) proposed a scoring model for awarding marks for students’ concept maps. However, having piloted it with trainee teachers’ concept maps I felt that it was not a useful method of analysis for this study, since although it enables you to arrive at a view on which concept map is best, the marks don’t tell you anything about what people know. Instead, I decided first to look for evidence of correct and incorrect propositions, as well as omissions, since I considered this information of interest to teachers.

Categories for coding students’ responses were written based on the A Level specification that the students had studied, taking into account the key words that had been selected, as well as my knowledge of what might reasonably be known by A Level students, based on my experience of teaching the topic in the past. For example, one relevant part of the specification lists the following (AQA, 2007, p 6):

“Constituents of the atom:
Proton, neutron, electron
Their charge and mass in SI units and relative units. Specific charge of nuclei and of ions. Atomic mass unit is not required.
Proton number Z, atomic number A, nuclide notation, isotopes.”

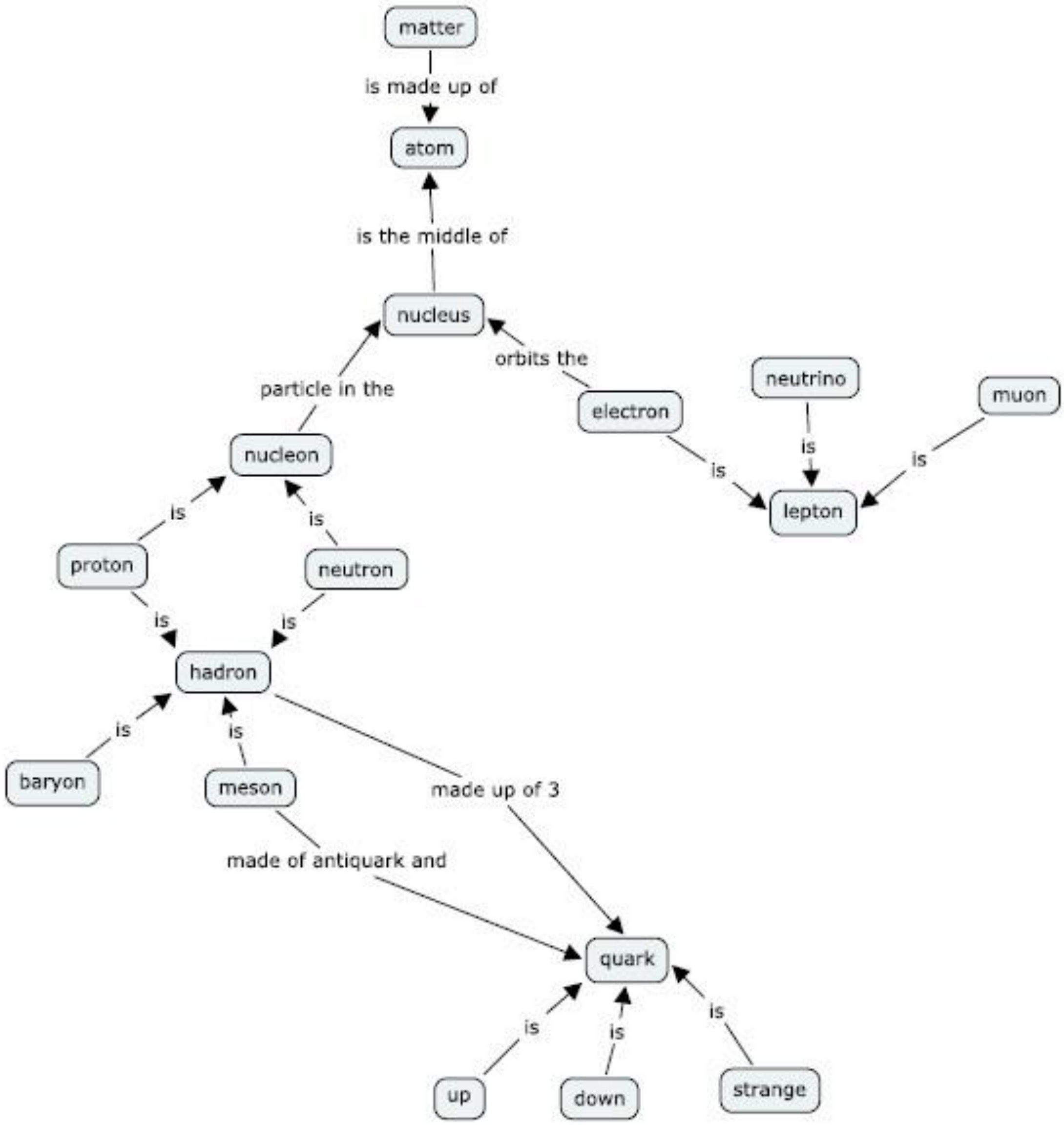
This section gave rise to the following categories for coding:

The proton is a constituent of the atom

The neutron is a constituent of the atom
The electron is a constituent of the atom
The proton is positively charged
The charge on a proton is +1.6 x 10^{-19} C
The neutron is neutral (or has no charge)
The electron is negatively charged
The charge on an electron is -1.6 x 10^{-19} C
The mass of a proton is 1.67 x 10^{-27} kg
The mass of a neutron is 1.67 x 10^{-27} kg
The mass of an electron is 9.11 x 10^{-31} kg
The mass of a neutron is similar to (or slightly greater than) the mass of a proton
The mass of a proton or neutron is approximately 2000 times greater than the mass of an electron
Proton number Z is the number of protons in the nucleus
Atomic number A is the total number of protons and neutrons in the nucleus

Results

An example of a student's concept map is shown in Figure 1. The map has been redrawn using a software tool for anonymization purposes.



Correct propositions

Table 1 shows propositions that were in line with the accepted view in A Level physics that were most frequently represented in students' concept maps. Propositions shown by 10% of the students (6) or more have been included:

Proposition	No. of students in school 1 (n = 21)	No. of students in school 2 (n = 38)	Total no. of students (n = 59)
Up is a type of quark	10	33	43
Down is a type of Quark	10	33	43
Strange is a type of	10	32	42

quark			
When a particle and its antiparticle meet they annihilate each other	13	23	36
Electron is a type of lepton	6	26	32
Baryon is a type of hadron	3	28	31
Meson is a type of hadron	3	28	31
Proton is a type of baryon	5	21	26
Neutron is a type of baryon	5	21	26
Baryons are made of 3 quarks	7	18	25
Muon is a type of lepton	5	20	25
Neutrino is a type of lepton	6	18	24
Mesons are made of a quark and antiquark pair	6	16	22
The proton is a constituent of the atom (or nucleus)	4	12	16
The neutron is a constituent of the atom (or nucleus)	4	12	16
The electron is a constituent of the atom	4	12	16
When annihilation takes place the mass of the particles is converted into energy in the form of photons	5	8	13
Mesons are made of 2 quarks	6	5	11
A neutron is made of	2	6	8

an up quark and two down quarks			
The antiparticle has the opposite charge to the corresponding particle	3	4	7
Hadrons are subject to the strong nuclear force	3	3	6
The proton is the only stable baryon	2	4	6
Leptons are subject to the weak interaction	4	2	6
A proton is made of two up quarks and a down quark	0	6	6

Table 1: The correct propositions included most frequently by students

The most frequent correct response was to identify the three types of quark that were listed in the specification (up, down and strange).

The idea that annihilation takes place when a particle and antiparticle collide was recorded by a majority of students in both schools. Fewer students represented a more detailed description of annihilation involving mass being converted into energy, however.

More than half the students knew that the electron is a type of lepton. Muons and neutrinos were also categorised as leptons by many of them.

The other element of the specification that was shown correctly by a relatively large number of students overall, and by a majority of students in school 2, was the meanings of the terms hadron, baryon and meson. This included knowledge of the number of quarks found in baryons and mesons. However, relatively few students included the detail of which particular types of quarks were found in neutrons and protons (which are both baryons). Similarly, some students represented the two-quark nature of mesons, without specifying that they are made of a quark and anti-quark pair.

Misunderstandings

I identified 220 propositions from the 59 concept maps, of which I considered 70 to be at odds with the material presented in the specification (AQA, 2007) and textbooks (Breithaupt, 2008; Trevillion & Priddle, 2001). Owing to the wide range of propositions created by the open-endedness of the concept mapping task, these were aggregated together by recording the number of incorrect propositions in each area of the topic that was seen to be causing difficulty. The topic areas which were associated with the greatest numbers of incorrect knowledge propositions (being expressed by 10% of the students, 6, or more) are shown in table 2.

Topic area	Number of instances of incorrect propositions
Leptons	20
Particles and antiparticles	14
Fundamental particles	12
Annihilation and pair production	7

Table 2: Areas of the topic with the largest numbers of misunderstandings

The most common difficulty that students had with leptons was not recalling that muon and tau particles are leptons. The concept maps suggested that many of these students thought that muon and tau particles were mesons. They were sometimes thought to be types of quark. Overall, the propositions revealing difficulties with in this area of the topic suggested that these students were confused about categorising particles as leptons, mesons and quarks.

This ties in to some extent with the area of the topic that I labelled fundamental particles – the predominant error here being that students indicated that everything is made of quarks. Leptons were recognised as being fundamental particles less frequently than were quarks. Fewer students were able to identify three leptons (e.g. electron, muon, neutrino) than were able to identify three quarks.

The most common proposition that could be interpreted as revealing a misunderstanding about particles and antiparticles was that ‘matter is made of particles and antiparticles’. However, this may just indicate a lack of clarity about terminology (since matter is made of particles and antimatter is made of antiparticles).

The concept maps also indicated that students were confused about annihilation and pair production. This was expressed in a variety of ways:

- Some leptons are produced by annihilation. (When particle, e.g. electron and antiparticle, e.g. positron collide they annihilate. They are not produced by annihilation.)
- Annihilation produces matter and antimatter. (Photons are produced, not matter and antimatter.)
- Annihilation produces hadrons and leptons. (It produces photons.)
- Pair production is when an electron with too much energy produces photons. (A correct example would be that a photon produces an electron and positron.)
- Pair production is when a photon with sufficient energy makes two particles that repel each other. (If an electron and positron are produced they attract one another owing to the fact that they are oppositely charged. The student appears not to have understood that they move in opposite directions in order to conserve momentum.)

Discussion and recommendations

Given that students should have been familiar with the idea that atoms are composed of protons, neutrons and electrons from earlier study, it is perhaps surprising that more of the concept maps didn’t include representations of related propositions, such as ‘the atom (or nucleus) contains protons’. A smaller proportion of students indicated this than were found to know about the substructure of the atom in Lynch and Paterson’s (1980) study (in which the students concerned were younger). This could be due to the difference in method, however, as the earlier study had used multiple choice tests. Further research on this topic could include follow-up interviews with some of the students who had done concept mapping, to find out whether this omission was indicative of a weakness in their knowledge, whether it was a weakness of the concept mapping method itself, or whether it was related to students' lack of familiarity with concept mapping.

Very few students (~4) made representations of the charge on the electron being negative and the charge on the proton being positive, which was also surprising given that they would have studied this in earlier years. Again, it would be interesting to carry out follow-up interviews, or to use a questionnaire to find out whether or not this is a good representation of the extent to which A Level students are aware of the charges on these particles towards the end of the first year of study. The omission could be because the students felt themselves to be limited to the concept words on the list suggested. Perhaps when using the concept mapping method again the words positive and negative, or charge could be added. If found to be a genuine reflection of students' knowledge, however, it may go some way to explaining why Taber (2012) saw only a weak understanding of electrical forces between the electron and the nucleus.

It concerned me that a number of students appeared to think that everything is made of quarks. I thought it a little odd that the exam specification expected the students only to know of three of the six quarks, but all of the leptons, and yet many of the students still appeared to think everything is made of quarks. Students also showed greater awareness of the different types of quarks than they did types of leptons. This study did not look at the teaching sequence used by the teachers, so this would be an area for further research – to find out whether or not the students' gap in knowledge here could be addressed by modifying the teaching. Based on my experience of teaching this topic in the Salters Horners A Level course using the Trevellion and Priddle (2001) textbook for reference, I would suggest introducing the standard model early in the teaching sequence, in order to help students to appreciate that both quarks and leptons are fundamental particles, and that there are six of each. The course textbook endorsed by AQA for the specification that the students in this study were following (Breithaupt, 2008) does not explicitly refer to the standard model. Additionally, Breithaupt (2008) introduces muons at the same time as introducing pions and kaons (having all been discovered through investigations of cosmic rays), which may explain why some students thought that muons are mesons.

I also found the students' confusion between annihilation and pair production interesting. Whilst on the one hand annihilation was represented correctly by a large number of students at the level 'when a particle and its antiparticle meet they annihilate each other' the more detailed responses tended to suggest that some students were unable to distinguish between annihilation and pair production. Again, this study did not look at the teaching sequence. However, inspection of the course textbook (Breithaupt, 2008) shows that the two processes are introduced on the same page. It might be better not to teach them concurrently, if this is what has happened. In this textbook (Breithaupt, 2008), annihilation is introduced in the context of PET scanning. Perhaps a different context could be used to introduce pair production, such as the interaction of X-rays with matter which used to be taught in the medical physics topic in some earlier A Level specifications (Muncaster, 1996).

A limitation of this study is that the students who took part were overwhelmingly male, largely because one of the schools was a single-gender boys' school. Improving gender balance is a current interest of the Institute of Physics (IOP, 2013). It would be interesting to carry out further research to ascertain whether or not there is any difference in approach to the concept mapping task for male and female students.

Barlow (1992) questioned whether it was a good idea to teach particle physics at A Level owing to concern about whether or not it could be understood prior to teaching about quantum mechanics. The outcomes of the concept mapping exercise lead me to have some sympathy for this view, as I think there is a danger of students being confused by the plethora of terms that they are asked to learn. The concept mapping exercise itself is something that I would recommend to teachers, however. One of the teachers of the classes in the study adopted concept mapping as a normal part of the teaching of this topic as a result of taking part. It need not be used as an exercise to be completed by individual students. White and Gunstone (1992) identify a number of purposes for concept mapping, which include promoting discussion. Perhaps by working in a group and talking about their different understandings of terms in the particle physics topics some of the students' misunderstandings could be overcome.

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