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Investigating the role of analogies as tools for teaching topics in modern physics

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Metaphors and analogies play a very important role in human thinking and perception (Lakoff & Núñez; 2000) and we use them frequently when trying to understand or explain complex concepts (Bjerregaard et al.; 1995). Hence, analogies to classical physics are often the method of choice in didactic approaches to teach modern physics. However, many of these models describe certain aspects of a phenomenon very well, but do no longer apply when describing the more complicated contexts of the phenomenon. Inconveniently, these models or analogies are very difficult to erase or substitute because of their apparent inbuilt logic and simplicity. Here, the aim was to investigate the role of such models and analogies when studying the basics of NMR spectroscopy. Thereby, it was also explored whether alternative strategies to use models and analogies could be developed.

Introduction

Learning is a constant search for meaning. In the process of learning, learners often attempt to simplify new experiences and compare it to old concepts (de Haan; 2005). This new simplified concept of what has been learned will then be applied to future examples and the concept will be expanded. This process is generally described as conceptual learning (Wiig & Wiig; 1999). The study of sciences is usually considered as an ongoing progress where new information can be readily understood in the context of older concepts. However, it can be argued that scientific developments such as Quantum mechanics or Einstein's theory of Relativity clearly show a discontinuity in the logic of sciences. In other words, for topics in modern physics, there exist certain epistemological breakpoints with classical physics and classical principles. Interestingly, the individual learner will overcome these breakpoints in a very individual manner due to their underlying personal psychological structure (Kuhn; 1969, p. 44). At such breakpoints, the use of institutionalised models or analogies that refer to concepts from classical physics can be a potential source of difficulties for students. First and foremost, instead of facilitating the epistemological break that is needed in order to be open for studying subjects in modern physics, often, these models do not impose the necessity of such breaks. Additionally, many of these models describe certain aspects of a phenomenon very well, but do not apply when describing more complicated contexts. Inconveniently however, these models and analogies are very difficult to erase or substitute because of their apparent logic and simplicity. Experiences with high school quantum physics teaching clearly show, how the overuse of such models based on analogies to classical physics hamper the students understanding of the subject at a higher level and as taught at universities (Euler et al.; 1999). Consistently, university teachers have to undo misconceptions and misinterpretations from previous teaching.

The course chosen to form the basis for the investigation is termed 'Protein Structure Determination'. In this course, master's degree students are amongst other methods introduced to NMR (nuclear magnetic resonance) spectroscopy and X-ray crystallography. The theory behind NMR spectroscopy is very challenging, and there exist various approaches and models to introduce NMR spectroscopy to the novice students. One of the favoured approaches is the so-called vector model, an model that uses arrows, representing the net magnetisation, being flipped around in a 3D coordinate system under the influence of external magnetic fields in order to explain certain pulse sequences. Another aspect of the vector model is that these "arrows", i.e. the net magnetisation, start "rotating" with individual frequencies within a rotating frame, which shall represent the radiation emitted from the various nuclei in a static magnetic field.

In this study, it was investigated whether it could be of help for the students' learning process if models for NMR spectroscopy using the traditional analogies to classical physics such as precession, torques and electromagnetic induction were omitted. Instead, the students were exclusively exposed to a qualitative view of NMR using approaches that try to visualise and apply the phenomenon (Rebello & Zollman; 1999). In detail, the focus of the teaching was set on practical exercises and real life-data. Furthermore, the course ILOs were designed to focus on how the phenomenon of NMR can be exploited to gain information about the properties of a protein on a molecular level instead of exposing the students to any detailed background theory. As part of the course structure, there is no final exam for this course. Instead, the final evaluation was entirely voluntary and based on various formats of open questions. Therefore, it was possible to design a non-performance based strategy for evaluation with a special focus on whether practical and/or qualitative foundations can form a better basis to promote the individual conceptual understanding.

Methods and Materials

In order to prepare a suitable teaching approach for the students, the guidelines according to "an instructional model aiming at a radical conceptual reconstruction" were followed (Kalkanis et al.; 2003). Formally, each course day consisted of a short introductory session to the day's subject (15-25 min), a 2h session of practical computer exercises with short breaks to summarise key points, and a 3h afternoon session with a journal club. For the journal club, students in groups of 2-3 were asked to present an article, which was then subject to group discussion. Articles were chosen so that they supported the day's message, but also contained an additional theoretical element, that could be discussed and explained in detail in cooperation with the presenting group. The presenting group was therefore given the opportunity to consult the supervisor prior to the presentation and informally discuss difficult issues they experienced when working with the articles.

Prior to the course, former colleagues were interviewed informally. A first questionnaire was given to the students during the first lecture, and a second one after the third lecture. Both questionnaires can be found in the Appendix (p.223). At the beginning of the third lecture, a mind map task was assigned (for the layout see Figure 18.1). After the course was finished, a focus group interview was conducted with 3 selected students according to their responses to the first questionnaire and the lack of response to the following two tasks.

Questions and assignments were given in open-ended formats. This resulted in a diverse response which did not allow statistical analysis and also might question the overall validity. However, this form of enquiry allowed that results were analysed phenomenographically (categorised in groups without referring to correctness) and contextually (responses were given

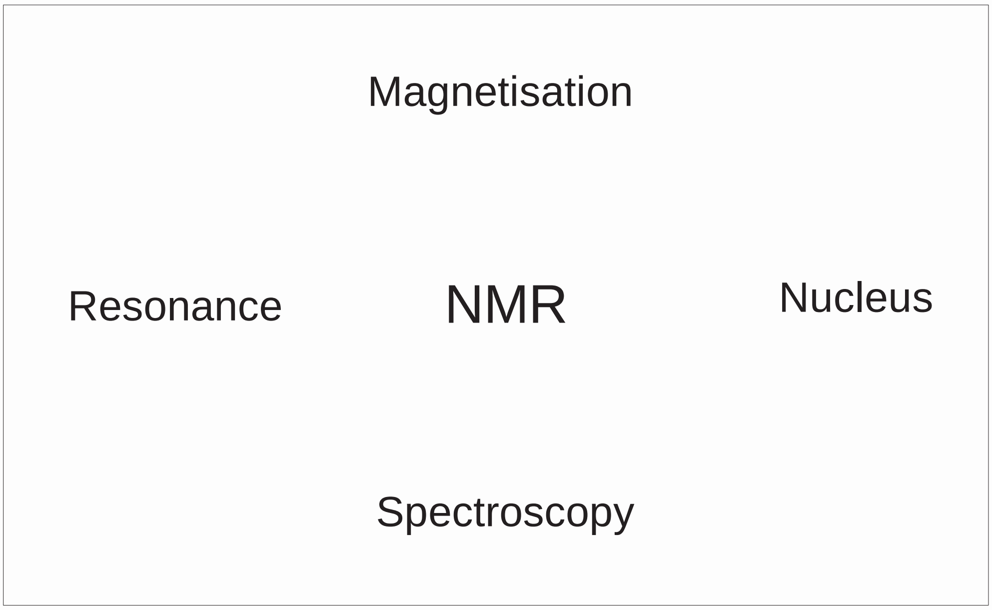

Fig. 18.1. Layout of the mind map task. Students were given these five words and the instruction to generate a spontaneous mind map with other individual expressions they were asked to set into relation to these five words.

in different concepts – what it has, what it does, what it is like – which provides information about the structure of mental models).

Results

A general feature of the course during the recent years has been the extremely mixed background knowledge. Before the first lecture, all 21 students were given a short questionnaire regarding their background knowledge and their motivation concerning the study of NMR spectroscopy. 17 students chose to answer this questionnaire. This served as a tool to gain insight into the composition of the course and highlighted the students' expectations. Roughly, students of the course PSD 2010 could be grouped into three groups: novices, intermediates and advanced. Novices stated that they had no experience with NMR spectroscopy, and had not taken the course 'Protein Science' in the third year of their bachelor program. The course 'Protein Science' covers certain aspects of NMR spectroscopy, but leaves the theory widely untouched. This course had been taken by the intermediate group, and some of them also stated to remember some NMR theory from an earlier course in organic chemistry. Advanced students had taken both courses and had used/will use NMR spectroscopy in their master project. In addition, these students had already been exposed to conversations with supervisors or experienced fellow students, and hence have already begun to shape their views and theories on NMR spectroscopy. The exact composition of the 17 members of the course who chose to answer the questionnaire can be found in figure 18.2A.

In the following, the students were themselves asked to choose their favourite way to approach the study of NMR spectroscopy. In detail, they could state whether they preferred a theoretical and mathematical or a more practical approach or a combination thereof. Interestingly, with the increase of background knowledge there was a certain correlation between the wish to study theory and mathematics and the insight that the theory is too hard to study in such a short course. Despite the clear wish for getting the theory explained, students with increasing background knowledge would therefore prefer to study NMR theory in a rather bite-sized manner. The novices, in contrast, were polarised into a very motivated group ("novice c"), that considered an early exposure to the theory a prerequisite for an adequate understanding and a strictly opposed group ("novice a“) hoping to for a more practical approach and the least possible theoretical way of studying NMR spectroscopy. For the exact distribution, see Figure 18.2B-D.

When asked for their usual sources to study NMR, novices mostly cling to the lecture notes and the recommended literature. Occasionally, they also quote Wikipedia as a good source for a general understanding. The confidence in standard textbooks vanishes quickly with the increase of experience, while the internet as a source wins drastically in importance. Students even seem to prefer much higher specialised articles over textbooks. The personal conversation with experienced students or supervisors also gains tremendously in importance. At the advanced level, the personal communication is clearly dominant when it comes to enquiring and understanding the theory behind NMR spectroscopy. This trend can be clearly seen from graphs E-G in Figure 18.2. This trend in combination with the lack of suggestions for a recommendable textbook, neither by students nor by experienced colleagues, clearly showed that the traditional ways for explaining NMR spectroscopy cause a lot of confusion among the students.

As an instrument to assess the progressive understanding of the students in the course PSD 2010, three methods were chosen. First, students were

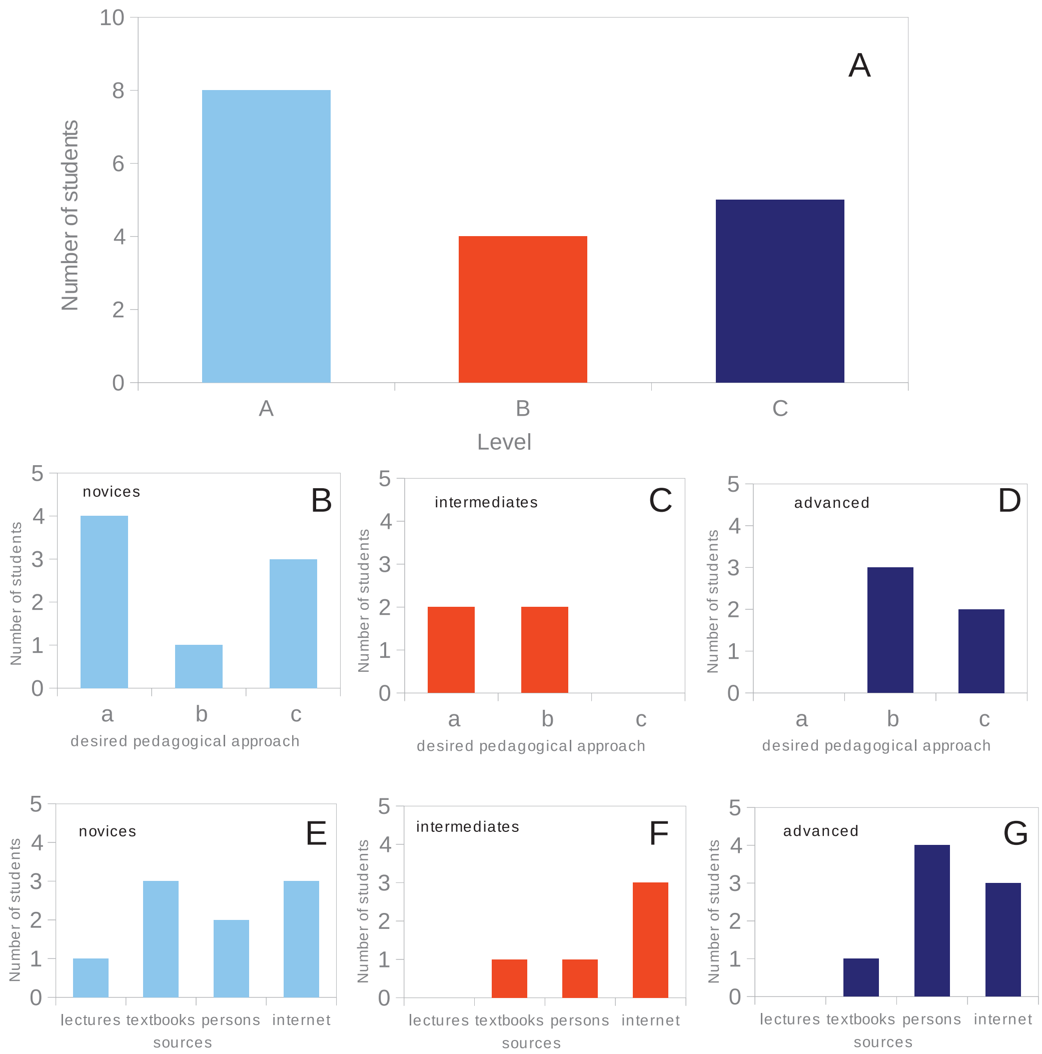

Fig. 18.2. Student background and expectations. 7 students were asked to provide information about other course attended that contained lectures on NMR spectroscopy. **A)** According to their responses, students were grouped into "novices" – no background, "intermediates" – have taken Protein Science A, B, or C, and remember NMR spectroscopy from organic chemistry lectures, and " advanced" – have taken both courses and use NMR spectroscopy in their bachelor and/or masters project. **B) – D)** Furthermore, students were asked about their wishes for a pedagogical approach to NMR spectroscopy: a) students that wished to study NMR spectroscopy by experiment, b) this group expressed a wish to hear about the theory, but were aware of, that it is difficult and hence wished for a slow and half-formal approach, and c) these students expressed a clear wish to study NMR theory on a theoretical and mathematical level. **E) – G)** Students were asked to list the usual sources they usually consult for self-studies. More than one answer was possible.

asked to create a mind map on NMR spectroscopy. Five students attempted to draw such mind maps, and despite several reminders, no students from the novice group were able to complete the task. Three mind maps were received from students from the group "intermediate" and two from the group "advanced". All five mind maps can be found in the appendix. In addition, two "expert" mind maps were collected from colleagues for the purpose of comparison. The mind maps have been summarised into three generalised mind maps which were grouped according to the individual levels in Figure 18.3.

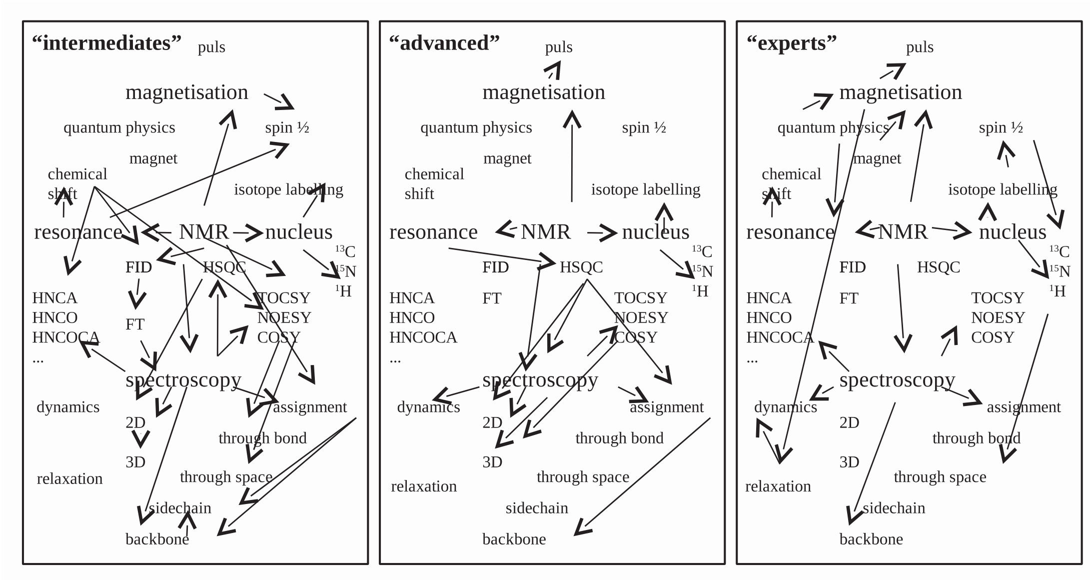

Fig. 18.3. Generalised mind maps from different levels of experience. "Intermediates" and "advanced": students grouped according to Figure 1**A**; "experts" refers to experienced people using NMR spectroscopy on a day-to-day basis for their research.

Common very interesting observations amongst the students are summarised first. Most interestingly, they all assigned high importance to the HSQC (heteronuclear single quantum coherence) experiment. In the mind maps, the term "HSQC" clearly stands separately and distant from other experiment types. This is also the experiment most relevant for protein biochemists and its use has been emphasised since the first day in the course. Another interesting observation was that all students managed to integrate "RESONANCE" into their mind maps. Interestingly, the teaching did not focus much on explaining resonance and if so then in a very non-theoretical manner. This indicated a certain process in the generation of own theoretical considerations. As expected, there was a high connectivity concerning the expressions “SPECTROSCOPY” and “NUCLEUS” since the teaching sat a clear focus there. In contrast to the “expert” group, the field “MAGNETISATION” again was left relatively unconnected, maybe marginally more connected in the “advanced” group. This again was regarded as a clear sign for the lack of a detailed theoretical understanding.

Some clear differences between the two groups could also be noticed. The group “intermediate” could clearly incorporate the key elements of the teaching, such as the Fourier transform, the FID, 2D, 3D, HNCO, HNCOCA, HNCA, as well as the expression “chemical shifts”. On the other hand, other expressions incorporated in the mind maps such as NOESY, COSY, were only introduced with minor emphasis towards the end of the lecture, mostly after the mind map task was handed out. Still, students also frequently tried to incorporate these expressions into their mind maps. This was seen as a clear sign for experiencing a more classical teaching approach prior to the course. Classical semi-theoretical approaches usually start to introduce multidimensional NMR via the NOESY and COSY experiments using the above described vector model. This historical way of teaching still persists even though the latter experiment rarely finds use in current practice. Finally, HNCA and HNCO, the multi-dimensional MNR spectra introduced in the second lecture of this course, were clearly assigned to the side of the word “RESONANCE” and were not connected to the word “NUCLEUS”. This was seen as a clear indication that the obvious connection from the artificial labelling of the protein to the facilitation of the assignment could not be made by the students.

Generally, mind maps of “advanced” students contained fewer words. Considering NMR experiments, they only mention NOESY, COSY, TOCSY (not emphasised at this stage during the course) and not the experiments used in the practical part (i.e. these students are still stuck in “the classical way” of studying NMR spectroscopy). The course program put special emphasis on chemical shifts, and the lack of the term “chemical shifts” in the mind maps of advanced students was realised with great surprise. In addition, they did not include any of the key elements presented to the students during the course, e.g. FID, Fourier transform, chemical shifts, HNCO, HNCA etc., neither did they connect the different type of spectra they mention to the word “assignment” (the “assignment” task was the major emphasis of the practical part which encompassed 1/3 of the course work). Instead, the students introduce a clear spatial separation between the two word groups considering various experimental procedures and various assignment strategies. This is surprising, as even the classical way of teaching NMR spectroscopy renders these two expressions the key elements when introducing the concept of multi-dimensional NMR and protein assignment. However, this separation can still be seen on expert level and might not be a lack of understanding but might also be seen as self-evident or likewise.

Interestingly, the students appear to have generated the mind maps in two groups of two students, as suggested by the remarkably similar layout of these pairs of maps. One of the pairs contained an "intermediate" and an "advanced" student. The most obvious difference between these two maps, despite a similar overall layout, is that the intermediate student has added the elements "chemical shift" and "Fourier transform" from the theoretical part of the teaching during the course. Another interesting observation from this pair, but also from the student pair "intermediate" student - "intermediate" student is, that certain words from the individual article presentations have found their way into the mind maps, such as "TROSY" or "natural abundance", subjects, which were both not emphasised in the actual lecture part.

Secondly, students were given questionnaires where they were asked to state their own opinion about certain aspects of, or requirements for, NMR spectroscopy in order to investigate their level of understanding. There was no response from the group "novices a" but three responses from the group "novices c", two responses from the group "intermediates", and again, two responses from the group "advanced". In general, answers looked very similar. This confirmed, that students from all levels were able to reach a similar level of fulfilling the course intended learning outcomes (ILOs). Students could reproduce the individual messages of the various theme days, and also to a certain degree formulate own opinions or argue about certain aspects of NMR spectroscopy. When asked about missing elements during the course, it was the "novices c" that claimed a general shortage of theoretical elements, while the advanced students considered the emphasis on article discussions when teaching the theory as "too repetitive". The intermediate group expressed great satisfaction with regards to the balance between the elements of the course. The confidence level in handling the literature and the general understanding of NMR spectroscopy had grown greatly in all three groups. While novice students were mostly expressing a better understanding of the general contents of articles, intermediate and advanced students also state that they gained much more confidence in interpreting the data and in the quality evaluation of published articles as such.

Concerning the general understanding, “novice” and ”intermediate” students seem to have a persistent misunderstanding of the word “isotope labelling”. While most seem to be aware of, that “^{13}C- or ^{15}N-labelled” samples are used, they do not seem to make the connection to the ^{13}C or ^{15}N isotopes, but rather connect the word “isotope” with labelling methods that resembles radioactive labelling. This could also be seen from the lack of connection in the mind maps between the different nuclei types and the different experiments types. In general, both groups could explain how NMR spectroscopy can be used and what it can be used for, and could also list certain advantages and drawbacks of the method. The “intermediate” group had also developed a certain ability to self-evaluate the facts they have learned and stated, that “impurities as such are not a problem for the measurements directly due to the ratio between the compounds and the isotope labelling of the protein of interest, but the impurities can indeed indirectly interfere (e.g. through interaction with the protein of interest) with the quality of the spectra”. From their answers, it can also be deduced that they must have started additional reading and have begun to shape their own ways of understanding the theory.

The group of “advanced” students clearly showed the ability to think autonomously and did incorporate additional thoughts and individual background knowledge into their answers. However, a very practical approach to the theory still persisted, which focused greatly on what the methods can be used for, not how the physical phenomena the different spectroscopic methods are based on resemble each other or can be distinguished. Due to their hands-on experience, they were able to answer the questions with much more practical insight.

Thirdly, the lack of a general theoretical introduction to NMR spectroscopy resulted in vivid discussions and explanations of theoretical elements of NMR spectroscopy on a direct level between the individual students and the teacher. Even though it was strictly avoided explaining NMR theory using the traditionally practised vector model, personalised explanations and analogies were continuously developed together with the students. As a result, many of the teacher’s experiences throughout these discussions were also considered for the final analysis of this study. Such “personalised” models included e.g. very mathematical considerations of the influences of different shapes of the FID on the appearance of the spectra after the Fourier transform. The FID as a tool was therefore proven very useful for a couple of students to describe certain aspects of relaxation. Another student showed a very good ability for abstract 3-dimensional visualisation and reasoning, and a mind model could be developed how chemical shifts and NOEs could be used indirectly to determine the structure of a protein. This lead to the student's insight, that we cannot visualise the 3D structure directly, as it is possible in methods such as microscopy, i.e. introducing the ability to break with a previous concept. A third group of students approached NMR data handling from a relatively abstract perspective that resembled data alignment methods. Interestingly, it has to be noted their journal club paper was also greatly covering protein sequence alignments prior to the NMR methods part. However, none of these individual approaches could be used to communicate the concept to the entire group of students, but mainly only showed fruitful results for the subset of students that initiated the respective conversation.

A final focus group interview focussed on a group of three students, that never expressed interest in studying the theory in order to see what kind of views these had formed on NMR spectroscopy ("novices a"). From the interview, it turned out that the students tried to study NMR spectroscopy before but failed to follow the old course right from the beginning. They confirmed that their theoretical understanding has not changed remarkably compared to prior to the course, but they could identify certain connections that they were not aware of before. They also stated that the NMR spectroscopic methods mainly used in organic chemistry differs greatly from the ones applied in protein sciences, and they expressed a great awareness that different teaching methods can help to make sense in the individual context.

The general impression was, that also in the group "novices a" the intended learning outcomes (ILO) have been met, and the three members of the group expressed a grown confidence in understanding and interpreting articles. They also stated that the combination of articles and computer exercises facilitated the understanding greatly. The students also discussed the possibility that difficulties in spatial thinking (Mitchelmore; 1980) especially by women, but also other student groups, could be a possible key issue for having problems with the classical models used in NMR teaching. They also stated that the possibility for them to create their own models and viewpoints, and the possibility for them to discuss these ideas on a very informal basis helped them best so far in the progress of understanding NMR theory.

Summary and Conclusions

When watching the students in the course and analysing the evaluation material, prior knowledge was identified to obstruct the incorporation of new knowledge at all levels and to overshadow the general perception of a subject. A good example here are problems with the term “isotope”, but also the different approaches to “mind maps” with different levels of background knowledge. Interestingly, each student appeared to approach NMR theory from a very different and individual perspective. Here, it was observed during conversations with the students, that their “first close encounter” with NMR spectroscopy has evidently greatly shaped the students’ view and approach towards the theory behind NMR spectroscopy. In the case of “novices” and “intermediates”, this “first close encounter” was given by the individual article presentation. For the “advanced” group, experiences prior to the course were identified to form the key elements.

In general, from the observations and conversations throughout this project, it can be concluded that it indeed can be dangerous to impose analogies and models on the students and give them a certain degree of institutionalisation. Traditionally, models and analogies are considered a fundamental tool for explaining complex and difficult concepts. Here, it can be concluded that the danger lies within the attempt to understand and follow a concept using foreign (i.e. not-your-own) models and analogies. It must be kept in mind, that models and analogies might be a great tool for the teacher and scientist to express thoughts and ideas. However, it is not granted whether these models and analogies are understood in the same context on the student’s side and do not lead to persisting misconceptions. As an example, one of the most remarking outcomes of the focus group interview was that a simple conflict such as male-female abilities of spatial visualisation might lead to a different perception of the standard models in use. Furthermore, it can be seen, that all students as individuals try to include their own personal encounters into their way of understanding institutionalised models and analogies. This is prone to create further confusion and diversion in discussions and conversations.

To summarise the outcome of the study, a practical and qualitative approach was very much welcomed by students with very varying background levels, and good learning progress was made through individual dialogues and hands-on experiences. The approaches to inquire problems in modern physics, in this case NMR spectroscopy, were found to differ in all individual cases. When omitting the more traditional models, it was noticed that this created much more awareness for the students own approaches to develop theories about the nature of the phenomenon. Great successes were made during the individual conversation with the students, where models and theories were not taught as a fact but individually developed and discussed in a very phenomenological approach. These approaches were found to be very unique for the individual student but also only seem to work for only one or few students. When attempting to use models or analogies developed during personal communications in front of the entire group, this was again found to generate confusion amongst students.

From these most essential observations of this study, it is suggested, that a certain institutionalisation of analogies and models should be avoided. Instead, models and analogies should be individually developed together with the students. Thereby, students should be given the chance to develop their own approaches individually and "test" them together with the teacher in order to evaluate and develop their understanding. Following such an approach, the teacher becomes an interpreter of these models and analogies, but also as a moderator who encourages the break with classical or historical thinking. In the future, teaching strategies need to be explored that incorporate the newly-gained awareness of individual conceptual approaches better into the course planning.

A Questionnaires

Questionnaire 1:

What is your background knowledge on NMR spectroscopy: OC/spectroscopy courses, protein science courses etc., books, others and what are the most important things you remember from these courses?

What was useful in previous teaching, what was difficult to understand?

Do/Did you use NMR spectroscopy in your master project?

When did you get started being interested in NMR spectroscopy?

Why are you interested in NMR spectroscopy?

What is usually your main source of information about NMR spectroscopy (persons, books, internet)?

Can you recommend any textbooks/webpages that you think are good/bad. Why do you think they are good/bad?

Is a proper and detailed mathematical introduction frustrating or helping? Why? Would you be interested in learning this at a later stage or right in the beginning?

Do other spectroscopical phenomena help you to understand NMR? Can you give an example?

Can you think of possible applications to you own project? Why?

Questionnaire 2:

What is your scientific background (bachelor in Biochemistry, Nano, Bio, Chemistry, etc.?

What did you miss in the course?

What was overemphasized or could be cut down?

Would you like to learn more about the various spectroscopic methods? Which methods and what?

How confident do you feel in reading papers on protein structure determination after the course (also compared to before?

Can you name any fundamental similarities and differences between the spectroscopic methods like NMR, X-ray, but also Fluorescence or CD?

Where do the limits of the two methods NMR spectroscopy and Crystallography lie?

What do you think of recombinant proteins and isotope labelling? Why?

How important do you think is it to have clean samples for these various methods? And why do you think so?

There are always several ways to measure the same things. How do you think the choice of experiments can influence your results? Examples?

All contributions to this volume can be found at:

http://www.ind.ku.dk/publikationer/up_projekter/2009-2-1/

The bibliography can be found at:

http://www.ind.ku.dk/publikationer/up_projekter/kapitler/2009_vol2_nr1_bibliography.pdf/