University Physics Students' use of Explanatory Models

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ABSTRACT

We have examined university physics students' use of models when explaining phenomena concerning the interaction between electromagnetic radiation and matter. A range of scientific models are available to explain the phenomena. The student sample is drawn from six universities in UK and Sweden. The sample students have difficulties in providing appropriate explanations for the phenomena. Few students use a single model consistently in their explanations of related phenomena. Students' use of models appears to be highly sensitive to the context in which the phenomena to be explained is presented to them.

1. INTRODUCTION

This project focuses on university students' use of explanatory models. There have been a number of papers considering teaching and learning in specific content areas of university physics [1-11], but not for the area of interactions between matter and electromagnetic radiation. We have performed an exploratory study in this area and looked at university physics students' explanations of certain phenomena. We examine the models that students use in their explanations, and consider the extent to which these models match the science models typically taught at this level. The phenomena were selected carefully with the following criteria. Explanations of the selected phenomena should normally not to be used as exemplars of scientific models within undergraduate physics education. The phenomena should represent well known contexts for the students. There should be a range of scientific models available to explain the phenomena. Some phenomena should be related in the sense that physicists would use one model in explaining them. Scientific models in this study are taken to represent the relationship between phenomena and models according to Giere [12], as shown in figure 1.

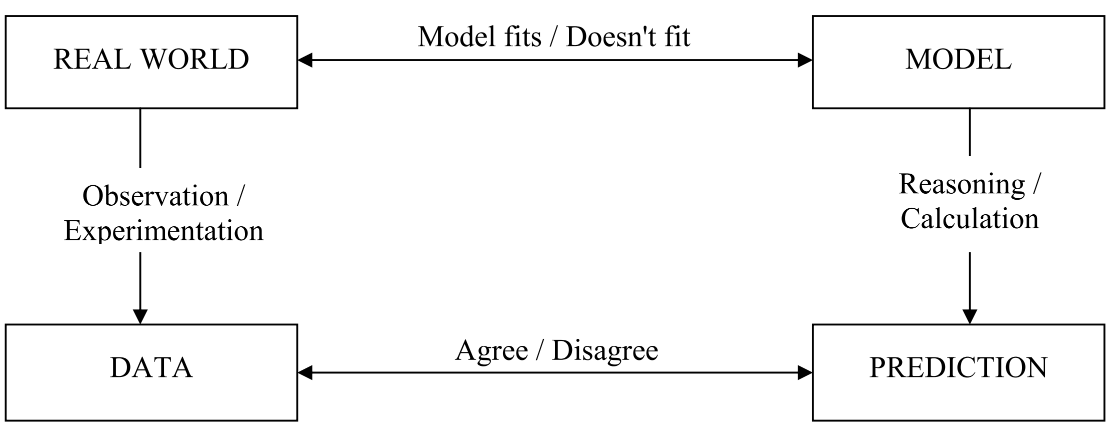

Figure 1. Links between the real world, models, predictions and data (adapted from Giere, [12]).

Phenomena are represented on the left-hand side of Fig. 1 as data gathered from the real world by observation and experimentation. On the right-hand side models and associated predictions provide explanations of phenomena. Predictions from the models are compared with data to provide an assessment of the effectiveness of explanatory models. It is also recognised that the model contains assumptions and approximations that limit the extent to which it can fully explain real world phenomena.

In this report we discuss the phenomena involving absorption of light in a transparent piece of plastic and in the solar atmosphere. Earlier we have published reports on the metal sequence [14] and the sunlight sequence [15]. The metal sequence covers the interaction of metals and electromagnetic radiation. The sunlight sequence constitutes of questions about the sunlight and atmospheric effects, both here at the earth and at the sun.

It has been suggested that acquisition of conceptual understanding in science is influenced by views about the nature of science. The concept area of interactions between matter and electromagnetic radiation has a large number of explanatory models available and therefore provides a valuable context in which to explore the relationship between university students' views about the nature of scientific knowledge and their development of conceptual understanding [15-17].

An additional interest informing the design of our study was the context-dependence of the models drawn upon by students. Engel et al. [18] provide evidence that many school age students do not apply conceptual models consistently across contexts. Mortimer [19] has suggested that rather than a single conceptual understanding, students exhibit a 'profile' of conceptual understandings. Other authors suggest that students hold a range of co-existing conceptions, of differing strength and status [20-21]. To explore these considerations our study includes an analysis of the consistency of students' use of models in explaining the interactions between metals and electromagnetic phenomena.

2. METHODOLOGY

The student sample is drawn from six universities in UK and Sweden. Students were asked to provide written explanations of phenomena. A written survey enabled us to use a sample large enough to reflect the range of models used in explanations by students at this level. Since the phenomena in the survey can be explained using a number of different explanatory models of differing degrees of sophistication, we chose to use open response questions in the survey. This ensured that students were not guided towards particular explanatory models presented to them. We also conducted follow up interviews, with demonstrations, for a subset of the student sample. Interviewees were asked to give a verbal response to each of the written questions. These interviews were used to assess the validity of the written survey responses, and to provide details of individual student's explanations across the phenomena presented in the survey.

3. STUDY DESIGN

We report findings for a subset of questions included in a broader survey of university students' explanations of phenomena involving the interaction between electromagnetic radiation and matter. All the phenomena are familiar to the students. The phenomena focused on in this report involve absorption of light in transparent pieces of plastic and the absorption spectrum of the Sun is discussed as comparison, henceforth called the *Absorption Sequence* (table 1). The full survey can be found in [13].

Initial versions of the written survey were piloted with 38 students. These students were in their first or second year of university in England or Sweden. In addition, pilot interviews were held with two Swedish and three English students. In the pilot interviews students were shown demonstrations. The survey and interview schedules were modified and shortened following piloting. The pilot interviews indicated that the written survey responses were providing a valid indication of students' views. However, piloting showed that the questions were too advanced for many first and second year students. In order to ensure that the students would have been introduced to all relevant models, third year university students were used for the final survey.

Table 1. The phenomena of the Absorption Sequence.

Short title	***Phenomenon to be explained***
Red plastic	Whether a red laser beam is impeded by a transparent piece of red plastic
Green plastic	Whether a red laser beam is impeded by a transparent piece of green plastic
Solar spectrum	The occurrence of absorption lines in a spectrum of the Sun

In order to reduce the impact of any specific teaching sequence our final sample included students at several universities. We collected 74 written responses from two universities in England and four in Sweden. We interviewed nine of these students: two in England and seven in Sweden. We aimed at a sample large enough to capture the main explanatory models used by students. We were concerned to establish that previous courses taken by these students included the models we identify as appropriate explanations of the phenomena presented in the survey.

4. RESULTS

4.1 An overview of students' responses

The investigated students have difficulties in providing appropriate explanations. Many students draw upon the Bohr model of *isolated atoms* when explaining light emission of a heated metal rod. These students tend not to recognise that atoms in metals interact to give an electronic structure very different from that of the isolated atom [13].

Some students draw upon the refraction of linear rays when explaining the colour of the sky on a sunny day [14]. Few students use a single model consistently in their explanations of related phenomena. Rather, students' choice of models is sensitive to the contexts in which the phenomena are presented to them. For instance, using models of the electronic structure of matter in unfamiliar contexts was clearly a challenge for the students in our sample [13,14].

To provide a preliminary overview of the data for the absorption sequence we conducted a normative analysis of students' responses to each of the questions. Each response was coded as 'appropriate', 'insufficient detail', 'inappropriate' or 'no response'. An *appropriate* explanation uses absorption as the dominant process, and results in that the laser beam, having propagated through the pieces of plastic, retains its direction. Responses coded as *'insufficient detail'* do not provide enough description of the matter-radiation interaction to satisfy the criteria for the ‘appropriate’ category. Statements leading to contradictions or not conforming to observations are coded as *‘inappropriate’*. These included responses referring to a wave model of light and using interference and/or diffraction in the explanation. Table 2 summarizes the results of this normative analysis for the *Absorption sequence*.

Overall, table 2 shows a low proportion of student responses giving an appropriate explanation, only about a third of the student sample for the red and green plastic. This is noteworthy given the weak criteria for an appropriate answer. The fact that absorption spectra often appear in introductory quantum physics courses could explain why a higher proportion of students use an appropriate model in this context, still it is less then two thirds of the students.

Table 2. A normative analysis of student responses for the phenomenon in the absorption sequence.

	Number of students (n=74)			
Short title	***Appropriate***	***Insufficient detail***	***Inappropriate***	***No response***
Red plastic	28	-	41	5
Green plastic	25	-	39	10
Solar spectrum	45	14	11	4

4.2 Models used by students in their responses

In order to examine the details of the models of matter-radiation interaction drawn upon by students we conducted a second, ideographic analysis. Data was examined with a commitment to reflecting each student’s position as written, rather than evaluating a particular response in terms of a set of normative criteria. The categories are described below. Each category is exemplified using survey responses.

AB Absorption process

A model of quantised absorption of photons is the dominant process. The photons are reemitted in all directions.
‘This time, the photons that make up the laser beam are being absorbed by the atoms. These absorptions excite the electrons, and so the energy is manifested as thermal energy. Thus the plastic heats up.’ (Survey, Green plastic)

EM Emission process

Excitations of bound electrons and emission is the dominant process, often preceded by absorption. Light beam does not retain direction and speed.
The plastic consists of atoms, whose electron transitions have a wavelength that matches exactly with the wavelength of the red light. An electron therefore absorbs this light and gets excited up to a higher level. Later, when the atom gets de-excited the radiation (same wavelength as the red light) will be sent out in all directions and there will not be as much light reaching the screen, thus we will see a weaker spot.’ (Survey, red plastic)

SC Scattering process

A photon model is used for the light and elastic scattering with free particles is discussed as the dominating process.
‘The red spot disappears from the screen, as the beam is simply scattered away by the red plastic. The photons are simply scattered in different directions by the atoms/molecules within the plastic’ (Survey, red plastic)

IN Interference process.

A wave model is used for the light, interference and/or diffraction is discussed in the explanation.
‘The wavelength will be in phase and they are therefore extinguished, since they have the same colour. The red plastic will stop the light from the laser. ’ (Survey, red plastic)

RE Refraction process

Here there is often no mention of particles and a linear ray model is used for the light.
‘The red spot on the screen changes position. The light beam will appear to deflect. Since green comes after red in the spectrum the beam will be refracted further on the screen.’ (Survey, green plastic)

Coherent responses not represented by any of the above categories were coded as *'other'* (OT). Responses from which it was difficult to understand what the student was saying, or which were very brief, were coded as *'vague response'* (VR). Finally, student responses stating that they could not provide an answer were coded as *'do not know'* (DK), and null responses as *'no response'* (NR).

The categorisation of statements in the interview transcripts matches that of the written responses for all the interviewees. This supports our view that the written survey responses as a whole are successful in capturing the general features of students' explanations.

Table 3 shows, question by question, the number of student statements from the written survey in each of the categories described above.

Table 3. Results from the ideographic analysis of the written survey responses.

Categories		*Red plastic*	*Green plastic*	*Solar spectrum*
AB	*Absorption process*	25	28	54
EM	*Emission process*	24	19	3
SC	*Scattering process*	6	7	1
IN	*Interference process*	6	3	7
RE	*Refraction process*	2	1	-
OT	*Other*	3	-	-
VR	*Vague response*	7	7	5
DK	*Do not know*	-	1	-
NR	*No response*	5	10	4
Totals		78*	76*	74

* Number of coded statements is higher than the number of students.

Table 3 shows that the inappropriate responses in Table 2 are partly accounted for by students discussing in terms of emission processes. The use of explanatory models is similar for the red and green plastic respectively. Notice, that there are strikingly fewer student discussing absorption processes for the pieces of plastic, compared to the solar spectrum.

In table 4 we show the number of student statements that refer to different kinds of particles. The number of statements that mentions atoms or molecules seems to correspond to the number of statements coded as absorption process in Table 3, but there is no correlation. Only about a third of the students use particles in their explanations for the red and green plastic. This is noteworthy since these are rather typical “particle processes”.

Table 4. Number of explanations where particles are mentioned.

Categories		*Red plastic*	*Green plastic*	*Solar spectrum*
AT	*Atoms*	21	18	45
MO	*Molecules*	4	3	8
EL	*Electrons*	11	13	-

OT	*Other*	1	-	2
NM	*Not mentioned*	32	31	18
NR	*No response*	5	10	4
Totals		74	75*	77*

* Number of coded statements is higher than the number of students.

Again the explanations for the solar spectrum stand out compared to the red and green plastic. Here, there is a correlation between the mentioning of particles and explanations coded as absorption process in Table 3.

4.3 Interview responses

In addition to providing validation of the written statements, student interviews also give more details of individual student's explanations across the phenomena in table 1. The following quote is part of the interview response from a student to the *Red plastic* question. The quote shows a student struggling to modify the explanation to make it fit the observed behaviour of the laser beam.

Student	*OK, since we have a red plastic it should absorb red light, since it has wavelengths matching the laser light. It will be deexcited and the light will be emitted in all directions. This means that we will have a weaker red dot.*
Interviewer	*OK, let us try it. If you concentrate on the red dot. What will …*
Student	*It is a very very little reduction in intensity, barely detectable change. This probably depends on some saturation effect.* **[Student sticks to explanatory model]**
Interviewer	*Ok, but what do you think happens within the plastic?*
Student	*The atoms in the plastic is excited by this particular wavelength, since it is red it has to have a matching transition. We see it as red, but maybe it is not exactly the same red colour as the laser light. And then the laser light excites the atoms in there and this absorption gives us a smaller intensity of the dot.*
***	[Discussion goes on a bit, but no change of explanation]
Interviewer	*We will use the green plastic instead, ok? We let the light shine through this one. What will happen then? First you tell me what you think.*
Student	*I think that nothing will happen. The light will go straight through, but there will be a little scatter. The spot will remain since there is no matching wavelength.*
Interviewer	*Lets try it.*
Student	*He he, It is completely opposite. The light disappeared.*
Interviewer	*Ok, the red dot disappeared for the green plastic*
Student	*Can it have anything to do with how the light is polarised? No, but, he he hmmm. We see this plate as green because it absorbs* ***all other*** *wavelengths* ***but*** *the green. That is why we see it as green. Therefore it has to absorb the red, that means it is the opposite case for the red one. I have difficulties with these colours …*
Interviewer	*Ok, but now we have done two experiments that might help you get it right, or*
Student	*It has to be so because this one (the red) let the red light through and therefore absorbed all other colours and that is why we see the red. Therefore the red light goes through it is not absorbed. For green it is the opposite case, it absorbs everything but green and therefore it absorbs the red laser light and we do not see the dot.*
Interviewer	*And how does it absorb the light, do you think? What is happening within the plastic when the light is absorbed.*
Student	*The plastic has matching transitions for all wavelengths except the green. The red light is absorbed. There is a transition that matches the red light exactly, the atoms get excited and then deexcited.*

This supports the suggestion by others [19-20] that students hold a range of co-existing conceptions. This student changes, or accommodates, the explanation, using another explanatory model or at least another aspect of the model to better explain what is observed.

4.4 Analysis of consistency

The design of the Absorption Sequence allows for tests of consistency in students' responses. The three questions present contexts in which the basic process is the same: *a frequency dependent absorption by atoms or molecules*. However, the wavelength dependence is different due to the fact that the molecules are bound in the pieces of plastic. We define a consistent response to these questions as one that uses the same explanatory model in all three explanations.

After having analysed the written responses we found that half of the students (37 of 74) use the same model in explaining the three phenomena. Only 12 of these 37 students gave appropriate responses, as defined earlier, the remaining 25 were consistently using an inappropriate model.

5. DISCUSSION

5.1 Subject matter knowledge

About a third of the university physics students in our sample were able to provide appropriate explanations for the phenomena of the *Absorption Sequence*. Table 2 shows that students struggled to articulate a coherent and complete explanation of the physical processes in the phenomena. Students struggle to explain these phenomena, involving the absorption of light by coloured pieces of plastic. They use a variety of models, including models not intended by teaching and the majority have not learned much about colour. We have not been able to ascertain the exact extent to which these students have been taught about colour. It is not a clearly defined part of the courses taken by the students, but it is occasionally covered by interested lecturers.

5.2 Context dependence of students' responses

Our study provides additional evidence for the claim that individual students are able to deploy a range of scientific models in a single content area [17-20]. Despite the relationship between the phenomena in our study only half of the 74 students in our sample deploy a single model across these contexts. Closer examination suggests that students' use of models is influenced by details of the context in which the phenomena are presented to them.

5.3 Implications for future teaching and research

As suggested by earlier studies of conceptual understanding the context dependence of student explanations has implications for research studies in this area. In particular, that a student draws upon a naive scientific model in one context does not necessarily mean that they cannot draw upon more sophisticated models in other contexts [19-20]. In the study reported on here, there were indications in some interviews that students were considering using a more sophisticated model than their original response, but they were clearly reluctant to do so in the interview setting.

This suggests that introducing students to models using a set of exemplary contexts will not necessarily lead them to draw on these models in other contexts. Of course, teaching using exemplary phenomena is an important first step as students begin to understand the key elements of a model. However, we suggest that such teaching needs to be followed by using the model to explain an extended range of phenomena. Of particular importance in a teaching sequence might be phenomena for which the model *cannot* provide a complete explanation, i.e. contexts in which limitations of the model resulting from inherent assumptions and approximations are exposed. Thus, also the explanatory models can be varied for a given phenomena and the existence of several models can be addressed in the teaching.

In this way students come to recognise the breadth of contexts in which particular models can be applied appropriately. Such teaching might be accompanied by more explicit teaching about the nature of models [12]. Many studies have highlighted the relationship between conceptual understanding in science and views about the nature of scientific knowledge [14-16]. Future studies could track the development of students' understanding in response to a teaching unit that incorporates both explicit discussion about the nature of models in science, and teaching about the many models of matter and their use in explaining the EM interactions. A key question for such a study would be the extent to which students are able to make links between these two foci of the teaching.

6. REFERENCES

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