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# A quantitative analysis of university student reasoning lines in the field of thermally activated phenomena

Onofrio Rosario Battaglia<sup>1</sup>, Benedetto Di Paola<sup>2</sup>, Claudio Fazio<sup>1</sup>, Nicola Pizzolato<sup>1</sup>, Dominique Persano Adorno<sup>1</sup>

<sup>1</sup>UOP\_PERG (University of Palermo Physics Education Research Group), Dipartimento di Fisica e Chimica, Università di Palermo, Italia

<sup>2</sup>GRIM (Mathematics Education Research Group), Dipartimento di Matematica e Informatica, Università di Palermo, Italia

**Abstract.** In this contribution we present a research aimed at studying the effectiveness of two workshops in improving reasoning skills in undergraduate students. Both the workshops are based on the Feynman Unifying Approach. A questionnaire containing six open-ended questions on the temperature dependence of evaporation of a liquid and of a chemical reaction was administered to the students of both groups before instruction. A second one, similar to the first but focused on a physical content different from both the pre-instruction test one and the content dealt with during the workshops, was administered after instruction. The responses to the pre- and post-instruction questionnaires are analyzed by using Not-Hierarchical Cluster Analysis methods and students' lines of reasoning about the proposed phenomena/situations are inferred in both the experimental and the control group. The implications on the efficacy of the two workshops in improving student explicative skills are discussed.

## 1. Introduction

Students' descriptive and explanatory skill development and use is a relevant aim of university programs, for a meaningful understanding of science, as well as for the development of professional competencies. Research has shown the relevance of characterizing the mental models (Greca & Moreira 2000, Johnson-Laird 2006) students use when asked to create or use explanations. It was shown (Clough & Driver 1986, Bao & Redish 2006) that students are often inconsistent in their use of mental models in situations that an expert would consider equivalent. As it is well known, in the construction process of explicative models inductive reasoning is involved, but an important role is also played by analogical reasoning (Duit & Glynn 1996). This involves the ability to see similarities and differences between a "source" (something perceived as similar to what we are going to analyze) and the "target" (the real phenomena that we are studying), and to generalize ideas and concepts already developed in a given context to different ones. This point is particularly relevant for undergraduate student science education, which aims to develop explicative and generalization skills in students, also by supplying them with unifying frameworks for the description and interpretation of natural phenomena only apparently different.

It is widely accepted that the need to identify differences and similarities between descriptive and explicative procedures, as well as the way these are used to generalize the results and account for real-world phenomena, can be met by introducing the students to the practice of scientific inquiry (AAAS 1993, Sadeh & Zion 2009, NRC 2012, Etkina 2014, Pizzolato *et al.* 2014). It would be interesting to study how the exposition of undergraduate students to an Inquiry-Based workshop focused on the well



know Feynman Unifying Approach (FUA)<sup>1</sup> to thermally activated phenomena (Feynman *et al.* 1963) can be effective in modifying the student lines of reasoning, redirecting them to explicative-like ones. Moreover, a comparison among these modified lines of reasoning and the ones that the students could develop by means of a different, more *traditional* approach to science learning, still based on FUA, but not explicitly focused on inquiry, would also be interesting.

In this paper, we discuss some of the results of a study involving a sample of undergraduate students in the second semester of their freshman year of the Undergraduate Program in Chemical Engineering. A questionnaire containing six open-ended questions on thermally activated phenomena was administered to the students of both groups before instruction. A second one, conceptually similar but focused on different physical content was administered after instruction. A quantitative analysis of the questionnaire responses was performed by using the k-means method (MacQueen 1967). It is aimed at allowing the researchers to group the students in intellectually similar subgroups (clusters) and at easily evidencing common patterns in the student responses to the questions. This procedure can help the researchers to infer the student lines of reasoning related to the creation and use of explanations in an unsupervised method (see, for example Sathya & Abraham 2013, Battaglia *et al.* 2017).

In the following sections, we present the research question addressed in this paper, a brief description of the analysis methods used and our results. Final comments about the implications of our results for the physics education of undergraduate students and suggestions for further developments are provided at the end of the paper.

## 2. Instruction and data collection

Based on the ideas discussed above, we chose to focus our workshops on the physics underlying the complex world of thermally activated phenomena, because it offers a good opportunity to understand and use unifying frameworks for the description and explanation of natural phenomena concerning apparently different fields of science. In particular, we focused on physics, chemistry and biology systems that can exist in two different states characterized by an energy difference  $\Delta E$  (Boltzmann 1909a, 1909b, reissued 1969) where the state transition is thermally activated by overcoming the potential barrier  $\Delta E$ . They are described by a unifying expression containing the Boltzmann factor,  $e^{-\frac{\Delta E}{kT}}$ , where T is the system temperature and k is the Boltzmann constant.

### Research Question

Our study is centred on the comparison of two learning environments. In them, undergraduate students are involved in the construction and use of explanations of thermally activated phenomena in a context oriented to the development of a unifying approach to natural phenomena. Taking into account these considerations, we formulated the following research question for this study: *How are the lines of reasoning applied by undergraduate students when asked to make sense of situations related to thermally activated phenomena modified by two different learning environments both focused on a unifying approach to natural phenomena?*

### Context, sample and methodology

Our research sample consists of 72 freshmen attending the Undergraduate Program in Chemical Engineering during the Academic Year 2014/2015 at the University of Palermo (UniPA), Italy. During the 1<sup>st</sup> semester of their Degree Program the students had attended general mathematics, physics and inorganic chemistry courses, and passed the exams. When selected to participate in our study, they were attending a 2<sup>nd</sup> semester Physics course dealing with the fundamentals of electromagnetism. The sample of students was randomly divided in an experimental group and in a control one (Myers & Hansen 2012), each made of 36 students. The 36 students of the experimental group attended

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<sup>1</sup> According to this approach, phenomena apparently different can be described and explained by using a same conceptual framework, i.e. the idea of two-level system and the mathematical description involved by Boltzmann Factor.

a 20-hour, strictly inquiry-based workshop posing their questions, designing and carrying out their own investigations, gathering information, collecting and analyzing data, providing explanations and sharing the results. The other 36 students (control group) attended a more traditional workshop, still based on laboratory and modelling activities but they have never been requested to follow the typical steps of an inquiry-based approach.

The reasoning deployed by the students when asked to explain phenomena, and relate them to the physics and chemistry they had already studied in previous courses, was studied before instruction by using a previously validated (Fazio *et al.* 2013), specially designed questionnaire. In the questionnaire, students were asked: 1) to discuss a real life situation (the evaporation of a water puddle at different environmental temperatures); 2) to describe the physical quantities contained in Arrhenius' Law; 3) to clarify the role of a catalyst in a chemical reaction; 4) to give a microscopic interpretation of the Arrhenius' Law; 5) to show generalization skills by finding other natural phenomena that exhibit temperature dependencies similar to the one highlighted by the chemical reaction speed, and 6) evidencing the similarities among these phenomena, particularly with respect to common physical quantities characterizing all the described systems.

The students in the experimental group then took a 20-hour workshop based on a Bounded/Open inquiry-based approach (Wenning 2005). The workshop dealt with a physical content (electricity) different from the one addressed by the questionnaire, but strictly related to the framework of thermally activated phenomena. The students in the control group, instead, took a course of equal duration and with the same instructors of the previous one. During this course the same physical content was dealt with, but this time the pedagogical approach was a more traditional one, still based on laboratory activities but not explicitly focused on Inquiry.

At the end of the workshops, a new questionnaire, validated by following a procedure similar to the one used for the pre-instruction questionnaire, and again focused on the study of student lines of reasoning about the use of descriptions/explanations in science, was administered to the students of both groups. This questionnaire was conceptually similar to the pre-instruction one, but was focused on physical/chemical contents (fluidity) not explicitly discussed before and/or in the workshop. In this questionnaire, students were asked: 1) to discuss a real life situation (the flow of oil in pipes at different environmental temperatures); 2) to describe the physical quantities contained in the viscosity expression  $\eta(T)$  according to Eyring's absolute rate theory; 3) to clarify the role of additives in oil industry; 4) to give a microscopic interpretation of the  $\eta(T)$  Law; 5) to show generalization skills by finding other natural phenomena that exhibit temperature dependencies similar to the one highlighted by the  $\eta(T)$  law and 6) evidencing the similarities among these phenomena, particularly with respect to common physical quantities characterizing all the described systems. All students in both groups completed the post-instruction questionnaire.

### **Specific content and Workshop description**

The two workshops dealt with the study of electric current in materials (conductors and semiconductors) and in vacuum systems (thermionic tubes). In particular, situations where the Boltzmann Factor (BF) can be used to describe electric conduction were analyzed. The experimental group workshop was divided into five phases, specifically following the 5E- model approach. These phases are briefly described in table 1. Also the control group activity was divided into five phases. Some detail can be found in table 2.

**Table 1.** *Inquiry Based workshop*

<b>Phase</b>	<b>Description of the activities</b>	<b>Hours</b>
<i>Engagement</i>	Presentation of the project and of IB approach. Discussion about conduction in ohmic conductors. Search for evidence of non-ohmic behaviour, as in semiconductor devices.	2
<i>Exploration</i>	Students acquired information and planned their activities in small groups, trying to pose questions they would answer during the experimental activities. They were introduced to the laboratory and encouraged to explore the measurement facilities and materials available, in order to design their own experiences. Students chose to address the electrical conduction process in vacuum tubes, which is easier to discuss and shows marked non-ohmic behaviour.	3
<i>Explanation</i>	Students carried out their research investigations, designed on the basis of the hypotheses and questions formulated during the explorative phase. They decided to study the anodic current vs. the filament temperature, to collect information about the values of concentration of electrons emerging from the filament. Mathematical modelling procedures were discussed in order to find a law to describe the concentration vs. temperature trend, which was found to contain the general BF expression. Some students searched for suitable models to make sense of their experimental evidence and the specific form of the suitable function they found, in particular with respect to the meaning of the quantity “energy” contained in the law’s exponential term. Some time was devoted to the analysis of an agent-based computer model related to the subject, built by using the NetLogo simulation environment ( <a href="http://ccl.northwestern.edu/netlogo/">http://ccl.northwestern.edu/netlogo/</a> ), which can easily simulate the interactions between a large number of elements. Students discussed a simulated mechanical model of a two-level system with the instructor. Particularly, they dealt with a large number of balls free to move on two connected planes, placed at different heights. Using the NetLogo simulation, it was possible to study the equilibrium distribution of the balls at the two levels and discuss the factors that influence this distribution. Finally, students compared simulation findings, experimental results and models explaining them.	10
<i>Elaboration</i>	Students searched for physical and chemical situations different from the ones discussed during the previous activities, whose experimental dependence on temperature gives evidence of a similarity with electrical conduction in semiconductors and thermionic tubes. A final scientific report was written by each group, with students sharing their ideas and preliminary results with the other participants.	3
<i>Evaluation</i>	Students presented the most significant findings obtained as a result of their experimental work and held a class discussion aimed at comparing and contrasting the results obtained by different groups.	2

**Table 2.** “Traditional” workshop

Phase	Description of the activities	Hours
1	The teacher gave a lecture to students, discussing with them the pedagogical methods (laboratory and modelling activities, group work and discussions) that were to be used during the workshop and describing the contents that will be dealt. Particularly, concepts regarding electric conduction in conductors and semiconductors were recalled and the dependence of resistivity on temperature was discussed.	2
2	The teacher discussed the basic topics related to electric conduction in vacuum tubes, presented as an easier situation with respect to conduction in semiconductors. The special relevance of the concept of minimum energy that electrons must have in order to participate to the conduction process in vacuum tubes and semiconductors was highlighted. In the particular case of semiconductors, the teacher discussed the energy band evidencing the role of the energy gap that electrons must cross in order to take part to the conduction process. The easier situation of conduction in a vacuum tube was presented and the related functioning mechanism was discussed in the light of Richardson law. This law was introduced because it allows the students to easily understand the relevance of a comparison between the thermal energy possessed by the electron and the threshold energy related, in this case, to electrostatic potential energy.	4
3	During this laboratory-based phase, the teacher first described the laboratory equipment, then presented to the students the experiments and the related measurements. He performed them, showing the results to the students and gave them some worksheets that they had to use in order to repeat the measurements, take note of the results and represent them in table and graphic form. The students measured the values of electric current and temperature and the concentration of electrons coming out from the vacuum tube cathode, in order to verify that these values are in accordance to the Boltzmann Factor formula.	6
4	The teacher showed to the students a NetLogo simulation, that is a mechanical example of a two-level system related to the Boltzmann Factor. The teacher made clear that this example can be related to the experimental situation they analyzed in the previous phase and allowed the students to run the simulation, modifying some parameters in order to obtain results that agree with their experimental values.	4
5	Students worked on their experimental and simulation results by following some worksheets given by the teacher and prepared a final scientific report to discuss with the teacher.	4

### 3. Data analysis

The quantitative analysis methods used in this study are based on clustering techniques. They allow us to subdivide the students in groups on the basis of their typical ways (or “strategies”) to tackle the questionnaire. Cluster Analysis (*CIA*) (Everitt *et al.* 2011) aims at classifying subject behaviours in different groups, or clusters. These can be analysed in order to deduct their distinctive characteristics and to point out similarities and differences between them. Here we will only use a specific non-hierarchical clustering method, called *k-means* (MacQueen 1967), as it allows the researcher to clearly individuate clusters that are also easily represented in Cartesian graphical form.



### Student answer classification

In order to apply CIA method it is necessary to categorise the questionnaire answers and code them. Due to the open-ended nature of the questions, after the questionnaires were submitted to the student samples the researchers independently read the students' answers in order to empirically identify the main characteristics of the different student records (the raw data). They agreed to independently construct a coding scheme by means of a phenomenographic approach (Marton & Booth 1997) to the student answer analysis, and through the identification of keywords that were relevant for the understanding of these records. During a first meeting, the selected keywords were compared and contrasted, and then grouped into categories based on epistemological and linguistic similarities that are actually the typical answering strategies deployed by the students when tackling with the questions. As a third step, each researcher read the student records again and applied the new coding scheme, by assigning each student to a given category for each question.

At the end of the coding procedures, two shared list of  $M$  answering strategies to be used for the subsequent analyses was obtained. More specifically,  $M_{\text{pre}} = 53$  answering strategies were obtained for the pre-instruction test analysis and  $M_{\text{post}} = 55$  ones were obtained for the post-instruction test analysis. Each of the  $N = 36$  students in each group was identified by two arrays,  $a_i$  and  $a'_i$  ( $i = 1, 2, \dots, N$ ) composed by  $M_{\text{pre}}$  and  $M_{\text{post}}$  components 1 and 0, respectively. In each of these arrays, 1 was assigned when the related student used a given answering strategy to respond to a question, and 0 when he/she did not use it. More detail of the procedure we followed to analyze data can be found in Battaglia, Di Paola & Fazio (2017).

### The k-means method

Non-hierarchical clustering analysis is used to generate groupings of a sample of elements (in our case, students) by partitioning it and producing a smaller set of non-overlapping clusters with not hierarchical relationships between them. Like other clustering algorithms, k-means requires that an index to measure the likeness between two elements be defined. In the case of k-means a metric must be defined to give a measure of the likeness between two elements (the students) by using the distance deduced by the metric itself. The distance can be defined as a function of the correlation coefficient between student couples (Di Paola *et al.* 2016, Battaglia *et al.* 2017).

The results of the k-means algorithm are plotted in a 2-dimensional Cartesian space where the points represent the students of the sample, placed in the space according to their mutual distances. As we said before, for each student, we know the distances between him/her and all the other students of the sample. It is, then, necessary to define a procedure to find two Cartesian coordinates for each student, starting from these distances. This procedure consists in a linear transformation between a  $N$ -dimensional vector space and a 2-dimensional one and it is well known in the specialized literature as *multidimensional scaling* (Borg & Groenen 1997). For this reason, the X- and Y-axes simply report the values needed to place the points according to their mutual distance and are reported in arbitrary unit. Then, the k-means algorithm starts by choosing the number,  $q$ , of clusters one wants to populate and of an equal number of "seed points", initially randomly placed in the same bi-dimensional Cartesian space where data are represented. The students are then grouped on the basis of the minimum distance between them and the seed points. Starting from an initial classification, students are iteratively swapped from one cluster to another. The students belonging to a given cluster are used to find a new point, representing the average position of their spatial distribution. This is done for each cluster  $Cl_k$  ( $k = 1, 2, \dots, q$ ) and the resulting points are called the cluster *centroids*  $C_k$  (Leisch 2006). This process is repeated and ends when the new centroids coincide with the old ones.

In order to define the number  $q$  of clusters that best partitions the sample on the basis of the student distances it is possible to use several methods. Here we used the so-called Silhouette function (Rouseeuw 1987). For each selected number of clusters,  $q$ , and for each sample student,  $i$ , assigned to a cluster  $k$ , with  $k = 1, 2, \dots, q$ , a value of the Silhouette Function  $S_i(q)$  is calculated.

$S_i(q)$  gives a measure of how similar student  $i$  is to the other students in its own cluster, when compared to students in other clusters. It ranges from  $-1$  to  $+1$ : a value near  $+1$  indicates that student  $i$  is

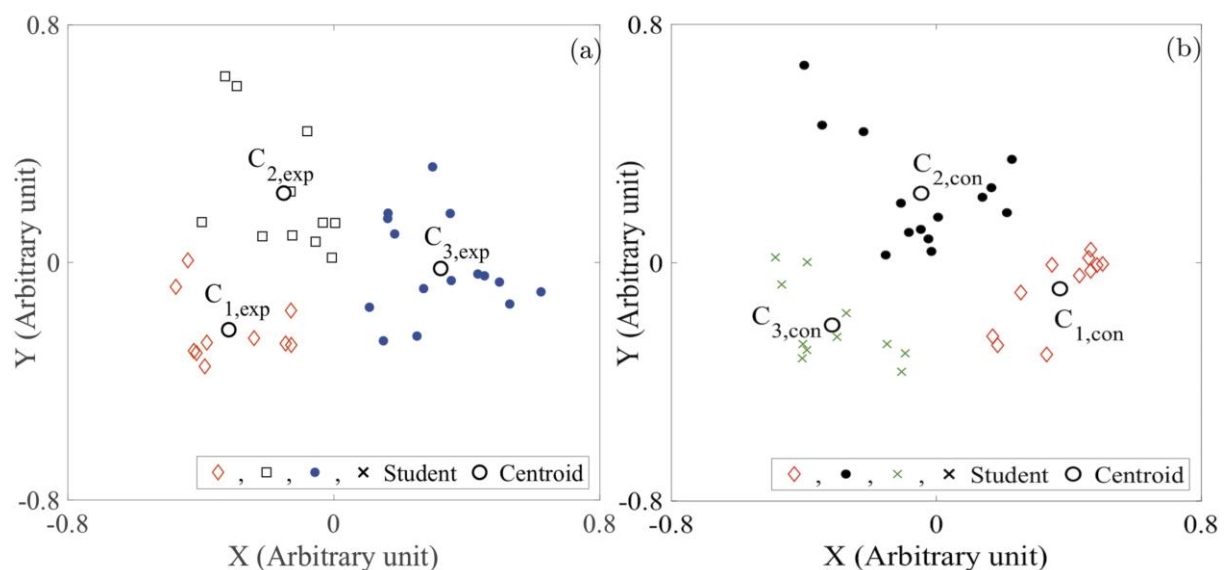
well-matched to its own cluster, and poorly-matched to neighboring clusters. If most students have a high silhouette value, then the clustering solution is appropriate. If many students have a low or negative silhouette value, then the clustering solution could have either too many or too few clusters (i.e. the chosen number,  $q$ , of clusters should be modified).

A remarkable feature of the centroid array is that it is composed by the answering strategies most frequently given by students belonging to each cluster (Battaglia *et al.* 2017). So, once the appropriate partition of data has been found, we decide to characterize each cluster of students in terms of its centroid.

#### 4. Results

All the clustering calculations on the student answers to the pre- and post-instruction questionnaires were performed using a custom software, written in C language. The graphical representations of clusters in both cases were obtained using the well-known MATLAB SOFTWARE (2015). By using the Silhouette method, we found that the best partitions of our samples are achieved by choosing three clusters in both the pre- and post-tests for the experimental and the control groups.

Fig. 1a and 1b show the representations of these partitions in 2-dimensional graphs for the pre-instruction test of experimental (a) and control (b) groups, respectively. The clusters show the partition of the samples into groups made up of different numbers of students. As said above, the clusters  $Cl_{k,exp}$  and  $Cl_{k,con}$  ( $k = 1, 2, 3$ ) can be characterized by their related centroids,  $C_{k,exp}$  and  $C_{k,con}$ , respectively. The same will be done for the clusters we find in the post-test analysis. The answering strategies most frequently applied by students in the clusters are synthetically resumed in tables 3 and 4.



**Fig. 1.** k-means graphs for pre-instruction test of the experimental group (a) and control group (b). Each point in this Cartesian plane represents a student. Points labeled  $C_{1,exp}$ ,  $C_{2,exp}$ ,  $C_{3,exp}$ ,  $C_{1,con}$ ,  $C_{2,con}$ ,  $C_{3,con}$  are the cluster centroids



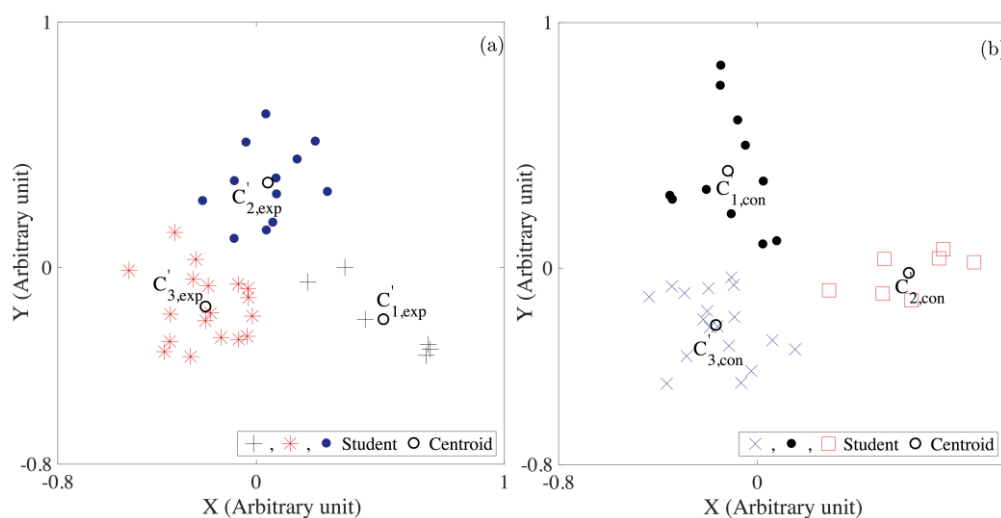
**Table 3.** An overview of results obtained in the experimental group pre-test

Cluster centroid	$C_{1,exp}$	$C_{2,exp}$	$C_{3,exp}$
Most frequently given answers	1) Only macroscopic description. 2) No description of the meaning of quantities. 3) A catalyst acts speeding-up a chem. reaction. 4) Arrhenius law is only mathematically described. 5) only a few phenomena from real-life and not relevant are mentioned. 6) Some similarities are found, $E$ or $T$ are mentioned.	1) verbal description and rough microscopic model given. 2) Some description based on real-life experiences. 3) A catalyst acts speeding-up a chem. reaction. A reference to energy gap is given. 4) Arrhenius law is only mathematically described. 5) Some related phenomena are described. 6) Some similarities are found, $E$ or $T$ are mentioned.	1) Some relevant description is given. No explanation. 2) Some quantity is described. 3) A catalyst acts speeding-up a chem. reaction. A simple reference to energy is given. 4) Arrhenius law is only mathematically described. 5) Some related phenomena are described, limited to the chemical context. Some math explanation. 6) Some similarities are found, not really relevant.
No. of students	10	11	15

**Table 4.** An overview of results obtained in the control group pre-test

Cluster centroid	$C_{1,con}$	$C_{2,con}$	$C_{3,con}$
Most frequently given answers	1) Some relevant description is given. No explanation. 2) Some quantity is described. 3) A catalyst acts speeding-up a chem. reaction. A simple reference to energy is given. 4) Arrhenius law is only mathematically described. 5) Some related phenomena are described, limited to the chemical context. Some math explanation. 6) Some similarities are found, not really relevant.	1) verbal description and rough microscopic model given. 2) Some description based on real-life experiences. 3) A catalyst acts speeding-up a chem. reaction. A reference to energy gap is given. 4) Arrhenius law is only mathematically described. 5) Some related phenomena are described. 6) Some similarities are found, $E$ or $T$ are mentioned.	1) Only macroscopic description. 2) No description of the meaning of quantities. 3) A catalyst acts speeding-up a chem. reaction. 4) Arrhenius law is only mathematically described. 5) only a few phenomena from real-life and not relevant are mentioned. 6) Some similarities are found, $E$ or $T$ are mentioned.
No. of students	11	14	11

Figs 2a and 2b show the results of the post-instruction tests for the experimental (a) and control (b) groups, respectively. The most frequently used strategies in the two groups are synthetically resumed in tables 5 and 6.



**Fig. 2.** k-means graphs for post-instruction test of the experimental (a) and control (b) group. Each point in this Cartesian plane represents a student. Points labelled  $C'_{1,exp}$ ,  $C'_{2,exp}$ ,  $C'_{3,exp}$ ,  $C'_{1,con}$ ,  $C'_{2,con}$ ,  $C'_{3,con}$  are the cluster centroids

**Table 5.** An overview of results obtained in the post-instruction test of the experimental group

Cluster centroid	$C'_{1,exp}$	$C'_{2,exp}$	$C'_{3,exp}$
More frequently given answers	1) the situation described and rough microscopic mechanism given. 2) relevant quantities found and physically described. 3) Additives are discussed in terms of energy gap. 4) Explanation in terms of molecular interaction is given. 5) some relevant phenomena are given, also not chemistry related. 6) Similarities are found. Activation energy is correctly discussed.	1) the situation described and rough microscopic mechanism given. 2) relevant quantities found and physically described. 3) Additives are described as speeding-up the flow. A rough reference to energy gap is given. 4) A rough explanation based on interaction between molecules is given. 5) some relevant phenomena are given, but only chemistry related. 6) Similarities are found. <i>E</i> and <i>T</i> are mentioned.	1) the situation is mathematically described. 2) relevant quantities found and physically described. 3) Additives are chemically described, in macroscopic terms. 4) The law is physically outlined. 5) some relevant phenomena are given, also not chemistry related. 6) Similarities are found. <i>E</i> and <i>T</i> are mentioned.
No. of students	6	12	18

**Table 6.** An overview of results obtained in the post-instruction test of the control group

Cluster centroid	$C'_{1,con}$	$C'_{2,con}$	$C'_{3,con}$
More frequently given answers	1) No good description, but molecular energy is cited. 2) relevant quantities are cited. 3) Additives are described as speeding-up the flow. 4) The law is mathematically described. No explanation given. 5) Some phenomena found, only related to Chemistry. 6) no clear answer.	1) Some description is given and molecular energy is cited. 2) relevant quantities are physically described. 3) Additives are described in macroscopic terms. 4) A rough microscopic model is given. 5) Some phenomena found, only related to Chemistry. Some explanation. 6) Some similarity found, $E$ and $T$ are found relevant.	1) Some description and a rough microscopic model are given. 2) relevant quantities are cited. 3) Additives are considered catalysts. 4) The law is mathematically described. 5) Some phenomena found, only related to Chemistry. 6) Some similarity found, but physical quantities not relevant are cited.
No. of students	11	7	18

## 5. Discussion and conclusion

The interpretation of *CLA* results mainly involves the identification of the typical features characterizing students' answers belonging to the same cluster as well as differences and similarities in answering strategies of students belonging to different clusters. On the basis of the obtained results, we can discuss the answer to our research question.

First of all, we note that similar behaviours can be detected in both the experimental and control group pre-test results, as the strategies in centroid arrays  $\bar{a}_{k,exp}$  and  $\bar{a}_{k,con}$  are almost identical. This is an expected result, as the experimental and control groups are random partitions of a unique set of students, and so should be roughly equivalent. The results show that both the students that attended the Inquiry-Based workshop (experimental group) and the ones that were exposed to a more traditional one (control group), before instruction mainly highlight the use of lines of reasoning in many cases not well suited to the study of physics. In fact, students of both the experimental and the control group seem to often use answering strategies which are inefficient to correctly find a microscopic functioning mechanism and to build proper explanations on the basis of the variables found as relevant for a phenomenon. In some cases ( $Cl_{2,exp}$ ), the phenomenon is explained in terms of a rough functioning mechanism. Very often, reference to a well-known mathematical model seems to stimulate a recalling procedure, i.e. a search in memory for real-life examples or studied concepts) that fit in with the formula, in some cases without a clear understanding of its physical meaning. Arrhenius law is always described in pure mathematical form, without a reference to its physical meaning. Finally, in many cases students highlight a lack of generalization skills, being limited in their answers to questions 5 and 6 to the context of studied subjects. However, in some cases (clusters  $Cl_{2,exp}$  and  $Cl_{2,con}$ ) a search for a common microscopic model for the situations recalled in answers to the last two question is present. All in all, we spot here a significant use of approaches based on common-type knowledge, even if in some cases in conjunction with higher level, descriptive strategies based on previous study or with a search for rough functioning mechanisms.

The results of the analysis of student answers to the post-instruction test, however, show that a difference between the experimental and the control group students, can be identified. In fact, 6 of the 36 students in the experimental group (cluster  $Cl'_{1,exp}$ ) are able to explain the situations and problems proposed in the questionnaire relating them to a functioning mechanisms based on the idea of thermal activation. Moreover, the students grouped in clusters  $Cl'_{2,exp}$  and  $Cl'_{3,exp}$ , although in some

cases still anchored to memories of past studies, showed to be able to explain the flow process in mathematical terms or by citing a functioning mechanism. They discuss the role of an additive by considering the energy gap concept but frequently do not relate it to interaction between molecules. However, in some cases the Arrhenius-like expression for viscosity is interpreted in terms of interaction between molecules. Finally, they seem to possess generalization skills, even if in some cases limited to familiar contexts.

Many of the students of the experimental group seem to have developed lines of reasoning about the Arrhenius-like phenomena that help them to make explanations coinciding with those of the accepted physical model and correct predictions of the behaviour of proposed situations perceived as similar. Moreover, the recognition of the common mathematical form in Arrhenius-like laws is in many cases linked to a better understanding of the functioning mechanisms behind these laws, something that was present at a substantially lower level in the initial phases of the workshop. In many cases, before the workshop activities students put the mathematical description in first place in their lines of reasoning. After the inquiry-based workshop activities, where they were encouraged to search for answers to proposed situations and phenomena by performing measurements and building models in a peer-to-peer set-up, many students appear to look at microscopic models that can explain the experimental evidence first, and then discuss and make sense of the mathematical law common form.

Some of the students of the control group also show a general improvement in reasoning with respect to the one highlighted in the pre-instruction results. In fact, students in  $Cl_{2,con}$  are able to correctly find and physically interpret the variables relevant in Arrhenius law, to discuss the role of additives in terms of the energy gap concept (although only at macroscopic level), to give an explanation of the flow processed in terms of interaction between molecules, and to find and discuss phenomena that are considered similar to the proposed one. On the other hand, the majority of the other students mainly base their approaches on a reasoning based on memory of past studied subjects or on macroscopic or mathematical explanation, without clear reference to the search for a microscopic functioning mechanism.

Our research shows that before the Workshops many of the Engineering undergraduates demonstrated mixed abilities with respect to the modelling of phenomena, initially perceived as different, but all analyzable in the common framework of the BF. Many students clearly highlighted the use of mixed-type reasoning strategies, with particular reference to ones that appear inefficient for building explications of the observed/proposed situations. These results are consistent with data from the literature (Hrepic *et al.* 2005, Bao & Redish 2006, Corpuz & Rebello 2011), that show that the lines of reasoning students deploy in creating explanations for proposed situations or observed phenomena can be eclectic and sometimes contradictory.

The results of a Bounded/Open inquiry-based workshop, focused on Boltzmann Factor based phenomena and using tools able to stimulate experimental analysis, as well as modelling at micro level, seem to highlight the efficacy of such an Inquiry approach in developing and improving the students' lines of reasoning. They appear to be redirected to the construction of mechanisms of functioning and to the identification of common aspects in apparently different phenomena, which may be an indication of a general framework in which phenomena explication can develop. A significant side effect of the IB workshop activities is a modification of the initial propensity of students to analyze a proposed situation by first taking into account the mathematical formulas and then trying to give a physical meaning to them. After the IB instruction many students seem to demonstrate the ability to discuss a proposed physical phenomenon by using a physical model that they perceive can be used to describe and explain the phenomenology. This often happens without having to refer to the mathematical formalism first, something that Vosniadou (1994) and Greca & Moreira (2002) pointed out as a key point to highlight a real comprehension in a particular field of physics.

On the other hand, the students that attended the more "traditional" workshop, still based on a laboratory and modelling approach focused on Boltzmann Factor based phenomena, but not Inquiry Based, after instruction showed improvement in their reasoning strategies. Some of them were able to correctly find and physically interpret the variables relevant in the proposed phenomena, to correctly

discuss the meaning of the energy gap and to give an explanation of the flow processed in terms of interaction between molecules. However, in many cases the majority of students involved in this workshop still highlighted forms of reasoning based on a search for analogy with studied subjects and laws and on a primary use of mathematics to make sense of the proposed situations.

We can conclude that both workshops were effective in improving the student reasoning strategies. However the IB learning environment, with the freedom it offers to the students to raise their own questions, to plan research and find different resources to answer the questions, seems to have been more effective in promoting cognitive skills oriented to explication of mechanisms of functioning than the more traditional one.

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