Uncovering and repairing teacher candidates' misconceptions about Miller indices with 3D models

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Abstract
The crystal structures play an important role in solid state physics class. It is necessary to have an ability to visualize crystal planes and directions. But physics teacher candidates find it difficult. The aim of this study was to evaluate the effect of teaching with the planes and directions placed on the real crystal structure model. The study was conducted with the participation of 13 physics teacher candidates. A questionnaire of 2 open-ended questions was to reveal the level of understanding and misconceptions of physics teacher candidates about Miller indices. In conclusion, we found that physics teacher candidates had difficulty in obtaining Miller indices and visualizing crystal planes and directions. Some of misconceptions revealed are: "The representation of negative indice is not known and negative indice is ignored while planes and directions are drawing", "The integer indices of plane and direction are separated by commas", "It is used to fractional numbers instead of whole numbers as Miller indices".

Keywords: Miller indices; Misconceptions; Content analysis.

Resumen
Las estructuras cristalinas juegan un papel importante en la clase de física del estado sólido. Es necesario tener la capacidad de visualizar planos y direcciones de cristal. Pero los candidatos a profesores de física lo encuentran difícil. El objetivo de este estudio fue evaluar el efecto de la enseñanza con los planos y direcciones colocados en el modelo de estructura cristalina real. El estudio se realizó con la participación de 13 candidatos a profesores de física. Un cuestionario de 2 preguntas abiertas tenía como objetivo revelar el nivel de comprensión y los conceptos erróneos de los candidatos a profesores de física sobre los índices de Miller. En conclusión, encontramos que los candidatos a profesores de física tenían dificultades para obtener índices de Miller y visualizar planos y direcciones de cristal. Algunos de los conceptos erróneos revelados son: "La representación del índice negativo no se conoce y el índice negativo se ignora mientras se dibujan los planos y las direcciones", "Los índices enteros del plano y la dirección están separados por comas", "Se usa para números fraccionarios de números enteros como índices de Miller".

Palabras clave: índices de Miller; Conceptos erróneos; Análisis de contenido.

I. INTRODUCTION

Everything that surrounds us is matter [1]. Of all matter surrounding us, a portion comprises materials. The development of novel technologies almost always relies on the use of newly available materials [2, 3]. It rapidly becomes clear that materials science is a vibrant, expanding area of research at the intersection between chemistry, physics, engineering, biology, and medicine [4].

The development of newly materials depends on more effective teaching and learning of basic material science knowledge. The aim of solid state physics for undergraduates in physics, applied physics, introductory materials engineering courses is to understand the microstructural basis for properties of materials and help students describe relations between a matter structure and its masroscopic properties. The one of most important topics in these courses is also the topic of crystal structures with a critical role.

A solid is said to be a crystal if the atoms are arranged in such a way that their positions are exactly periodic [5]. Understanding the behaviour of crystalline solids is easier than that of non-crystalline matters since the entire crystal can be reproduced translating from a small volume of the unit. If we know all of mechanic, electrical and thermal properties in unit, it can be described to these properties in the whole of crystal structure.

In the process of instruction on crystal structures needs to develop an ability to visualize two-dimensional projections of differently oriented planes and directions for different crystal structures. However, teacher candidates often have difficulty visualizing basic crystal structures, which can lead to mistake in determining other important symmetry features in the crystal.

It is known misconceptions that students' knowledge gaps and skill gaps from personal experiences and their prior knowledge as developed from academic courses [6, 7, 8, 9, 10, 11, 12, 13]. Misconceptions are difficult to change and may affect how learners process new information and data [14, 15, 16]. Hence these misconceptions should be diagnosed for effective learning and teaching has to take students' existing knowledge into account [17, 18, 19, 20].

Some researches about crystal structure, packing and symmetry are about determination of impacts of innovative technologies, using an alternative plan view and misconceptions of students or text-books [3, 6, 10, 11, 21, 22]. In these studies, there are not obtaining and drawing of crystal planes and directions with Miller indices.

This study is aimed to determine the change of understanding level and misconceptions of physics teacher-candidates with open-ended questions about crystal planes and directions. The questions we hope to answer with this investigation are: 1) whether physics teacher candidates draw two-dimensional projections of differently oriented planes and directions with Miller indices; 2) whether it can be determined the Miller indices for given a plane in crystal structure.

II. METHOD

In this study, action research design is preferred to reveal perceptions and misconceptions. Action research is a process in which participants examine their own educational practice systematically and carefully, using the techniques of research [23]. The reason behind preferring the research method become more effective when teachers and principals encouraged to examine and assess their own work and then consider ways of working differently [24]. Researcher giving solid state physics class preferred in this method. In this study, to teach about Miller indices, in solid state physics course, was to use real crystal structure model established by physics teacher candidates personally. The physics teacher-candidates were asked to place the various directions and planes drawn in two dimensions on the board into their own three dimensions crystal structure. The researcher was checked whether these directions and planes were placed correctly, sometimes walking around class. The researcher asked the physics teacher candidates to construct new knowledge in their own mind. In this process, learner physics teacher candidate in improvisation of instructional materials makes them exposed to creativity, innovation and curiosity, all of which are fundamental to teaching and learning of science [25]. Otherwise, it is aimed to increase the impact of teaching via the different senses of the physics teacher candidates.

A. Participants

The participants consisted of 13 physics-teacher-candidates in 2016-2017 summer semester. It was carried out with the candidates to have taken solid state physics course. Physics teacher candidates were enumerated as [T] and adding row number.

B. Data Collection Tools

Qualitative data collection tool is used. A questionnaire that included 2 open-ended questions is used in this study; it is given in the annex. Two questions were prepared by the researcher. Following the preparation of the questionnaire, validity of the questions in terms of content and purpose of the research was checked by two experts in the field of solid state physics.

C. Analysis of the Data

Findings of the research were obtained by an open-ended questionnaire. Teacher-candidates- responses and remarks were encoded by researcher, then grouped unanimously to be analyzed as sound understanding (SU), partial understanding (PU), partial understanding with specific misconceptions (PS), misunderstanding (MU), and no understanding (NU) [26].

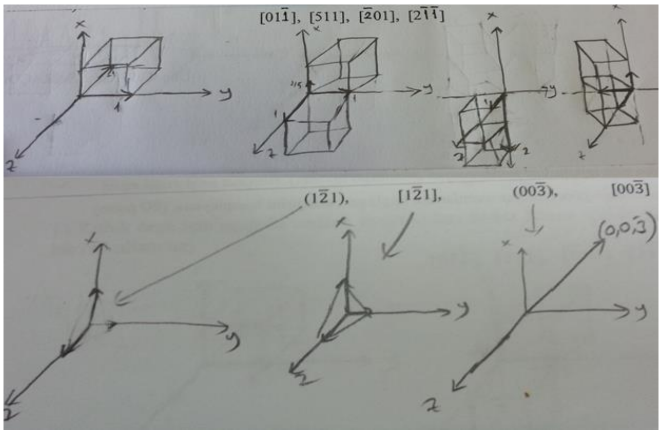
The data obtained from the questionnaire were analyzed qualitatively by content analysis, and results of the analysis were supported by direct quotes from the physics teacher-candidates statements [27, 28, 29].

III. RESULTS

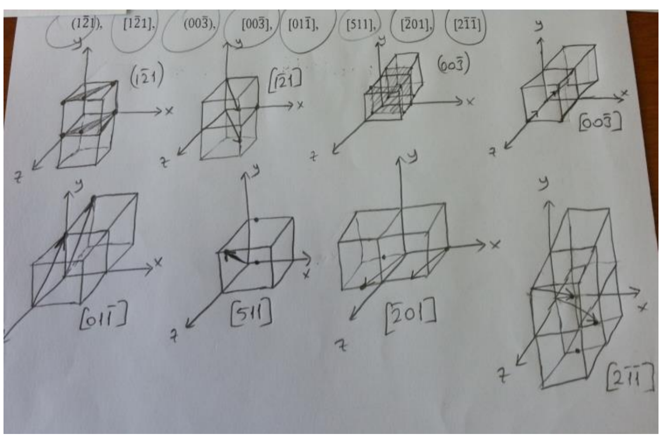
Findings obtained from the questionnaire regarding crystal planes and directions were grouped and interpreted: (1) the drawing of crystal planes and directions, (2) the obtaining of Miller indices. The degrees of understanding of Miller indices concept were considered to be on ordinal scales. It was shown points to each level in a manner similar to the intellectual development scores. The "no understanding" level (NU) could be assigned 0 point, the "misunderstanding" level (MU) could be 1 point, the "partial understanding with specific misconceptions" level (PS) could be assigned 2 point; the "partial understanding" level (PU) could be assigned 3 point, the "sound understanding" level (SU) could be assigned 4 point [26]. In this paper, PS and PU levels were also divided sub levels, respectively, from 2 to 3 and from 3 to 4 into equal parts.

A. The drawing of crystal planes and directions

The orientation of planes and directions in a crystal structure are specified by giving its Miller indices. The Miller indices of the plane and direction are indicated by the notations (hkl) and [hkl] where h, k, and l are reciprocals of the plane with the x, y, and z axes, respectively. The crystal direction and plane notation are made up of the lowest combination of integers and represents unit distances rather than actual distances. A [222] direction is identical to a [111], so [111] is used. Fractions are not used [30].



(a)



(b)

FIGURE 1. Examples of the [T_{11}] physics teacher candidate responses with the drawing of crystal planes and directions. a) Before application, at misunderstanding level b) after application, at sound understanding level.

It was investigated whether physics teacher candidates could correctly draw the planes and directions with Miller indices in the first question. Only one physics teacher candidates [T_{11}] gave the exact correct answer after application as given in Fig. 1b; whereas the same teacher candidates answered the first question with misunderstanding level (Fig. 1a). The understanding level of physics teacher candidate [T_3] is partial understanding with specific misconceptions both before and after application, but it is observed to decrease on her level as shown Fig. 2. After application, it was observed both planes and directions ignoring all of negative indices in her drawing. Negative indice is identified with a bar over the negative number instead of a minus sign. This situation did not take into consideration by teacher candidate [T_3]. It has been determined that [T_3] cannot distinguish negative symbol, but the difference of plane and direction notations. Unfortunately, there are deficiencies in the concept of the plane and direction with Miller indices, the cognitive process has not been successfully and the existing schema contain defects [31, 32]. The understanding level of teacher candidate [T_7] has been stable. Except for above mentioned candidates, the another teacher candidates have shown a positive change as shown Fig. 2. Although they have generally the same level (PS), there is an increase in the lower level. The representations of physics teacher candidates's planes and directions are more accurate and misconceptions are less.

The mean value of class is 2.29 after application although it is 1.48 before application. The change of understanding levels is showed in Fig. 2 and Table I shows the misconceptions of the physics teacher candidates with understanding levels.

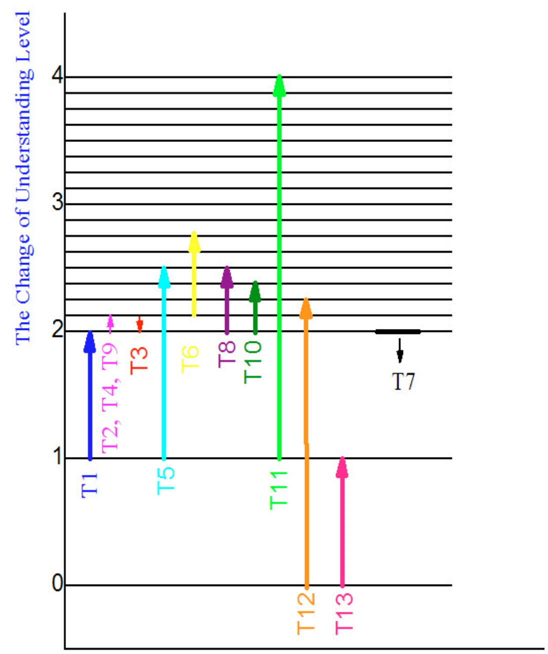


FIGURE 2. The change of the physics teacher candidates' understanding level.

B. The obtaining of Miller Indices

If we want to obtain the Miller indices of a given plane, it requires the following steps:

1. At this point the crystallographic plane either intersects or parallels each of the three axes: the axes; the length of the planar intercept for each axis is determined in terms of the lattice parameters a, b and c.

2. The reciprocals of these numbers are taken. A plane that parallels an axis may be considered to have an infinite intercept, and, therefore, a zero index.

3. If necessary, these are multiplied by a scalar to insure that is in the simple ratio of whole numbers. The

integer indices, not separated by commas, are enclosed within parentheses, thus: (hkl) [33].

Before application, physics teacher candidates were either at the NU or MU level and the mean value of class was 0.54. It was determined that they were confused about how to solve this problem. Unfortunately, the obtaining of Miller indices, before and after application, physics teacher candidates did not answer this question at SU level. Therefore, it can be said that they have not have domain-specific schemas [31, 34]. After application, while four out of thirteen teacher candidates showed improvement at PU level, the other four candidates were at PS level as shown Fig. 3. Before application, the understanding level of physics teacher candidate [T_7] was no understanding level (Fig. 4a). After application, but it was observed to increase on his level as shown Fig. 4b and Fig. 3. After application, the mean value of class is 1.99. It is shown analysis of obtaining of Miller indices at Table II.

TABLE I. Analysis of the drawing of crystal planes and directions.

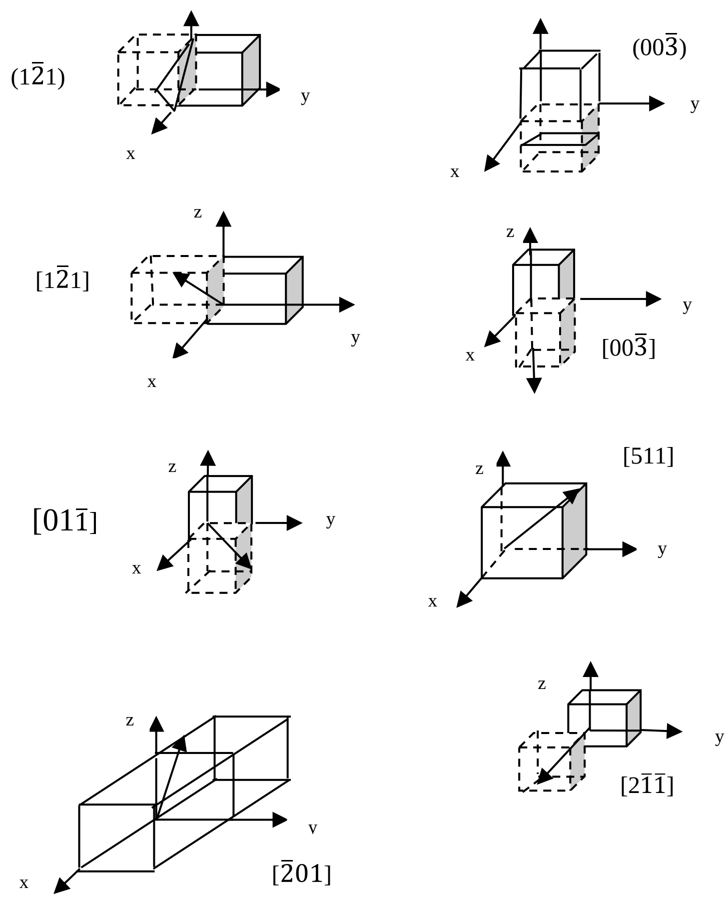
Understanding Level	Encoding	f (Before)	f (After)
SU		-	1
PU	. It can be drawn some of six planes and two directions.	-	-
PS	. The notation difference of plane and direction is unknown. . The representation of negative indice is not known and negative indice is ignored while planes and directions are drawing. . The integer indices of plane and direction are separated by commas. . It is used to fractional numbers instead of whole numbers as Miller indices. . For correct representation of plane and direction, the required quantity of unit cell is not added in sketch. . The plane with zero index, parallel to the axis, is not considered to intercept at infinity.	**8**	**11**
MU	. The axes are not be determined in accordance with the right-handed coordinate system.	**3**	**1**
NU	. Explanations are unrelated to the subject or unanswered.	**2**	**-**

TABLE II. Analysis of the obtaining of Miller Indices.

Understanding Level	Encoding	f (Before)	f (After)
SU	**a)** $\frac{x}{a}=\frac{1}{2}$, $\frac{y}{b}=\frac{1}{4}$, $\frac{z}{c}=\frac{1}{3}$ $\frac{a}{x}=2$, $\frac{b}{y}=4$, $\frac{c}{z}=3$ **(243)** **b)** $\frac{x}{a}=\infty$, $\frac{y}{b}=\infty$, $\frac{z}{c}=\frac{1}{2}$ $\frac{a}{x}=0$, $\frac{b}{y}=0$, $\frac{c}{z}=2$ **(002)** **c)** $\frac{x}{a}=\infty$, $\frac{y}{b}=1$, $\frac{z}{c}=1$ $\frac{a}{x}=0$, $\frac{b}{y}=1$, $\frac{c}{z}=1$ **(011)** **d)** $\frac{x}{a}=\frac{1}{2}$, $\frac{y}{b}=\frac{1}{2}$, $\frac{z}{c}=1$ $\frac{a}{x}=2$, $\frac{b}{y}=2$, $\frac{c}{z}=1$ **(221)**	-	-
PU	. It can be derived some Miller indices of four planes. . The integer indices of plane and direction are separated by commas.	-	4
PS	. The Miller indices for given planes are determined by using alternative method. . It is formed to fractional triplet $\frac{a}{x}, \frac{b}{y}, \frac{c}{z}$ instead of $\frac{x}{a}, \frac{y}{b}, \frac{z}{c}$. . The notation difference of plane and direction is unknown.	-	4
MU	. The planes with parallel to the axes, are not considered to intercept at infinity.	7	4
NU	. Explanations are unrelated to the subject or unanswered.	**6**	**1**

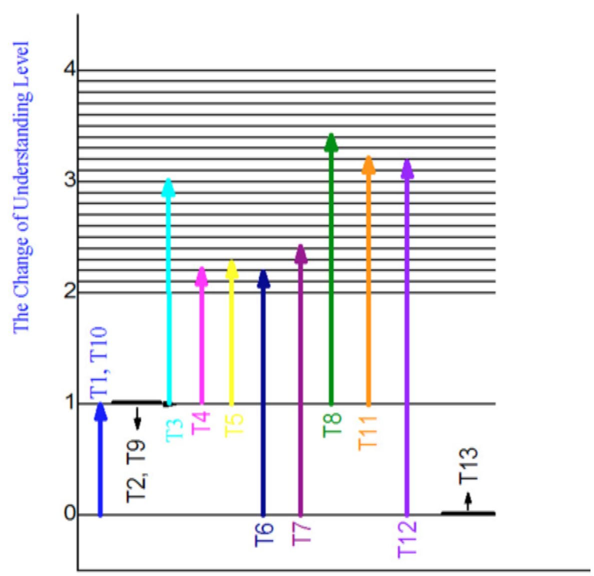
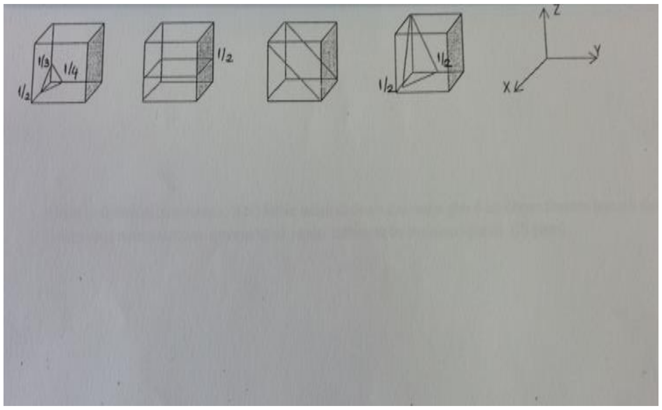
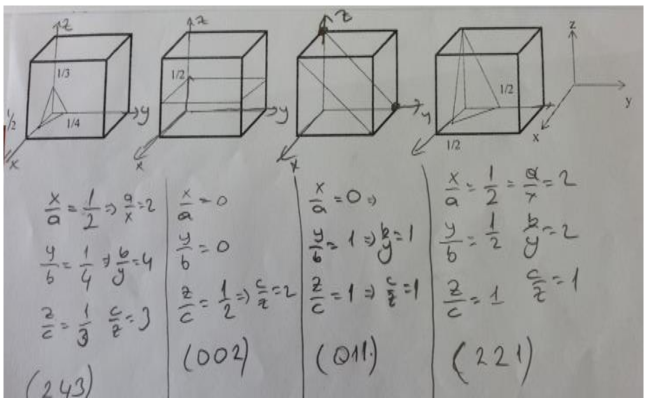


FIGURE 3. The change of the physics teacher candidates' understanding levels.



(a)



(b)

FIGURE 4. Examples of the physics teacher candidate [T7]' responses a) before b) after application.

IV. DISCUSSION AND CONCLUSION

In this study, it was evaluated that the understanding level and misconceptions of physics teacher candidates before and after instruction. It was investigated the effect of using real crystal materials on the learning of Miller indices concept. For the first question about drawing of crystal planes and directions, only one teacher candidate was able to fully draw given planes and directions. The change of the mean value in class is 0.81. It was found to increase about the understanding level of physics teacher candidates except for one of them. It was also determined misconceptions as "The notation difference of plane and direction is unknown", "The representation of negative indice is not known and negative indice is ignored while planes and directions are drawing", "The integer indices of plane and direction are separated by commas", "It is used to fractional numbers instead of whole numbers as Miller indices", "For correct representation of plane and direction, the required quantity of unit cell is not added in sketch", "The plane with zero index, parallel to the axis, is not considered to intercept at infinity".

From physics teacher candidates, it was expected to obtain the Miller indices through the other open-ended question, but for four different cubic unit cells. None of the physics teacher candidates could answer the question at level of sound understanding both before and after the instruction. The change of the mean value in class is 1.45. There is no change in the level of understanding of three physics teacher candidates. Misconception is revealed as "it is formed to fractional triplet $\frac{a}{x}, \frac{b}{y}, \frac{c}{z}$ instead of $\frac{x}{a}, \frac{y}{b}, \frac{z}{c}$".

Teaching with the highly interactive cloud-classroom techniques and visualization materials can be used to student's misconceptions and baseline knowledge of Miller indices.

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APPENDIX

Dear teachers, this test aims to evaluate your knowledge on ***"Miller İndices".*** The answers you provide will not have any effect on your course grades. Your answer sheets will be used within the research being conducted, and your name will be kept confidential in accordance with the codes of ethics. For validity of the research, it is very important that you answer all questions. Therefore, please do not leave any question blank. Thank you for your interest, and good luck.

Name & Surname:

1. Please construct planes and directions given below with Miller indices within a new cubic unit cell.
$[01\bar{1}]$, $[511]$, $[\bar{2}01]$, $[2\bar{1}\bar{1}]$

$(1\bar{2}1)$, $[1\bar{2}1]$, $(00\bar{3})$, $[00\bar{3}]$

2. Please determine the Miller indices for four different the planes shown in the accompanying sketch as below.