A review of three levels of chemical representation until 2020

S D Luviani*, S Mulyani and T Widhiyanti

1Program Studi Pendidikan Kimia, Universitas Pendidikan Indonesia, Jl. Dr. Setiabudi No. 229, Bandung 40154, Indonesia

*siscadwiluviani@upi.edu

Abstract. This article is a review articles on three levels of chemical representation until 2020. The method used in this research is document analysis. We obtained 72 articles published within 11 years (therefore, 2009-2020) that discussed the level of chemical representation. The results obtained were 50.67% of researchers using the term macroscopic, submicroscopic, and symbolic levels which were different from the original ideas of Johnstone. In addition, we found 15 new terms for 3 levels of chemical representation. Furthermore, the scope of macroscopic, submicroscopic, and symbolic levels becomes richer and broader.

1. Introduction
The three levels of chemical representation first introduced by Johnstone [1,2] have an important role in chemical education. The three levels consist of macroscopic level, submicroscopic level, and symbolic level [3,4]. The three levels are depicted by a triangle called the Johnstone’s triangle by the researchers. Student’s ability to explain chemical concept at each level and to make relation between them are important to understand chemical phenomena [5,6,7]. The use of macroscopic, submicroscopic, and symbolic representations simultaneously is proven to reduce students’ alternative conceptions in teaching and learning chemical concepts [3]. These three levels may appear simple and obvious to expert chemists, but they contain a lot of new or unfamiliar information to novices [8]. Therefore, the three levels of chemical representation turned out to be a source of difficulty for students [2].

Students' ability to use three levels of representation and difficulties in using them are still reported in current research [9,10,11,12,13,14,15]. This can be caused by students having less experience at the macro-level, having misconceptions at the submicroscopic level, and lacking understanding of complex conventions used at the symbolic level [4]. In addition, students often fail to integrate the three levels shown by their fragmented understanding like a missing puzzle piece [16,4]. This relates the ability of teachers who cannot convey representations clearly and cannot move between the three [17,16]. Even Talanquer [18] states that there are prospective teachers who are not critical of the existence of 3 levels. Therefore, teachers need to have a good understanding of the nature and scope of the level of chemical representation so that they can apply it in the learning process of chemistry. Likewise, for researchers who will apply 3 levels of representation in their research.

Researchers who apply 3 levels of representation in their research, they are able to understand the nature and scope of chemical representation levels well. For example, in compiling the interview guidelines, Allred & Bretz [12] can decide on the type of representation he uses in the interview, whether it is at the submicroscopic or symbolic level. Likewise, researchers who reported the ability of students to use 3 levels of representation and difficulty in using it [9,10,11,12,13,14,15]. In their study, researchers can map student understanding at the macroscopic, submicroscopic and symbolic levels. In
addition, researchers who want to know the existence of three levels of representation in textbooks [19,20], can map the representations presented in books into macroscopic, submicroscopic, or symbolic levels. In developing media and learning methods based on multiple representations to help students use 3 levels of representation [21,22,23,24,25,15], researchers can also map the types of representations used in media or their methods to these three levels. Therefore, when researchers or instructors use three levels of chemical representation, they must have sufficient knowledge about these three levels so that they are able to analyze the nature and scope of these three levels.

Until now, three levels of chemical representation have been adapted by researchers. Researchers sometimes have their own interpretations in explaining these 3 levels. Different adaptations and reinterpretations can cause confusion for teachers or researchers who are still unfamiliar with 3 levels of chemical representation [18]. This confusion can complicate analysis of coverage from 3 levels [18]. Therefore, in order for researchers / teachers to obtain sufficient knowledge related to 3 levels of chemical representation, we summarize the various term of representation level within 11 years (2009-2020) and describe the scope contained in these three levels of representation from various views. Gilbert & Treagust [4] have also shown various levels of representation terms since they were introduced by Johnstone [1], but only until 2009.

2. Methods
The purpose of this study is to summarize the various term of representation level within 11 years (2009-2020). In addition, we describe nature and scope of three levels of chemical representation from various views until 2020. The method used in this study is the document analysis [26]. Figure 1 show three phases of this study.

![Flow of study](image)

3. Result and Discussion
In this study, we will summarize and discus about various views of terms three levels of chemical representation until 2020. Based on 75 articles which we have reviewed at phase 3, we identified the terms used by researchers. Based on Table 1, the terms macroscopic, submicroscopic, and symbolic are most widely used by researchers within 11 years with a percentage of 50.67%. The terms are different from the Johnstone’s idea. Therefore, it is used to discuss their scope in this study. Furthermore, we found 15 new terms of three levels of chemical representation which is shown in note column in Tabel 1. In the following, we describe the scope of macroscopic level, submicroscopic level, symbolic level and the relationship between them from various views until 2020.
Table 1. Terms used by authors in 2009-2020

| No | Terms                                                                 | Number of Authors | Percentage (%) | Note |
|----|-----------------------------------------------------------------------|-------------------|----------------|------|
| 1  | Macroscopic, Submicroscopic, Symbolic                                 | 38                | 50.67          |      |
| 2  | Macroscopic, Microscopic, Symbolic                                    | 8                 | 10.67          |      |
| 3  | Macro, Submicro, Symbolic, Multiple, Hybrid, Mixed                     | 5                 | 6.67           |      |
| 4  | Macroscopic, Particulate, Symbolic                                    | 5                 | 6.67           |      |
| 5  | Chemical phenomena (experiential level), Macroscopic conceptualisation, Submicroscopic conceptualisation | 2                 | 2.67           | New  |
| 6  | Submicroscopic, Symbolic, Textual                                     | 2                 | 2.67           | New  |
| 7  | Macro & Entangible, Symbolic & Mathematical, Molecular & Invisible    | 2                 | 2.67           | New  |
| 8  | Macroscopic, Particulate                                              | 1                 | 1.33           |      |
| 9  | Phenomenology, Model, Symbolic                                         | 1                 | 1.33           | New  |
| 10 | Macroscopic, Microscopic, Symbolic, Algebra                           | 1                 | 1.33           | New  |
| 11 | Macroscale, Nanoscale, Symbolic                                        | 1                 | 1.33           |      |
| 12 | Applied chemistry, Sociochemistry, Critical-reflexive chemistry       | 1                 | 1.33           | New  |
| 13 | Experiential, Macroscopic, Submicroscopic, Visualization              | 1                 | 1.33           | New  |
| 14 | Macroscopic, Microscopic, Symbolic, Process, Quantum                  | 1                 | 1.33           | New  |
| 15 | Macroscopic, Microscopic, Particulate, Symbolic                       | 1                 | 1.33           |      |
| 16 | Macroscopic/Doing, Submicroscopic/Thinking, Symbolic/Communicating, Activity | 1 | 1.33 | New |
| 17 | Macroscopic, Microscopic, Mathematical, Experiential                   | 1                 | 1.33           | New  |
| 18 | Macroscopic, Symbolic, Particulate, Multiple, Hybrid, Mixed, Integrated, Combined | 1 | 1.33 | New |
| 19 | Experiential, Macroscopic, Relation experiential– macroscopic, Sub-microscopic, Relation experiential/macroscopic– sub-microscopic | 1 | 1.33 | New |
| 20 | Experiences, Model, Visualisation                                     | 1                 | 1.33           | New  |
|    | **Total**                                                              | **75**            |                |      |

3.1. Overview of macroscopic level

Previously, Talanquer [18] had also explored various kinds of researcher's perceptions about the macroscopic level that still occur today. Although referring to Johnstone [1], the researchers explain the macroscopic level in different ways.

Macroscopic level covers the actual phenomena that we experience in everyday life or laboratory [16,5]. Gabel [7] emphasizes the level of macroscopic as *sensory*, which can be seen, smelled, touched or felt [2,27,28,18]. Even Lin, Son, & Rudd [29] who use the word *macroscale*, emphasize this level only include phenomena that is experienced through the senses.

Contrast with Lin, *et al.* [29], Gilbert & Treagust [4] argue that chemistry learning does not begin by looking at the world and all its complexities. Macroscopic level were formed by the concepts and ideas that are used to represent properties of material [30,4,6,31]. Some researchers distinguish phenomena and macroscopic levels directly [32,33,34]. The phenomena which is observed directly is called the experiential level. At the macroscopic level, phenomena at the experiential level are reconceptualized so they contain scientific ideas.

Another researchers reveal macroscopic level is a phenomenon that only experienced by students in the classroom and the laboratory [35,36]. Macroscopic level is different from phenomena in everyday life. Whereas if chemical phenomena is related to student’s daily lives, it can motivate students to learn [16]. Even *Human Element is* suggested as a fourth component, to emphasize the need to link chemistry with student experience in everyday life [37,38]. In addition, this suggestion can encourage scientific literacy and limited public understanding of the role of chemistry.
At a time when *nanoworld* can be explored, phenomena that students can experience directly not only be obtained from inside and outside the classroom, such as the use of scanning *tunneling microscopy* and *optical tweezers* [18]. This causes confusion to categorize the phenomena into macroscopic or submicroscopic level. Therefore, Talanquer [18] used the word *experiences* that include descriptive knowledge about substances and processes chemical obtained directly (through the senses) or not (using instrumentation).

Based on this description, the macroscopic level has been used by many researchers but has different meanings. In fact, the term macroscopic level can cause confusion so that it is replaced with new terms. Macroscopic levels can also be the basis for developing new levels that are broader than macroscopic level, such as those developed by Mahaffy [37] and Sjostrom & Talanquer [39]. However, there is researcher who does not use the macroscopic level as part of the level of representation.

Textual representation replaces the position of the level of macroscopic [40]. In his study, Corradi, Elen, & Schraepen [40] states that the level of representation consists of textual, submicroscopic and symbolic representation. Textual representation is very important because it can help students who struggle to translate the submicroscopic and symbolic representation which are abstract for students.

### 3.2. Overview of submicroscopic level

Submicroscopic level are used to explain phenomena at the macroscopic level [1,41,7,35,42,18]. The explanation at this level involves particulate level of matter, such as molecule, atom, ion, electron, kinetic, structure, particles movement [43,27,6,5,44]. In addition, Gabel, Samuel, & Hunn [43] argue that submicroscopic level also includes a model. Some researchers propose the term model whose position is equivalent with submicroscopic level. This model is built from very small entities such as atom, molecule, ion, electron, etc. [4,18]. Models can be used to describe the structure, composition, and mechanism of chemical systems. Other researchers use the term submicroscopic representation which has the same meaning with the model.

Explanation at the submicroscopic level need to be represented [45,29]. Submicroscopic representation can be in the form of 3-dimensional or 2-dimensional molecular model, image, and computer animation, *ball-stick* model, and *space-filling*. Even the researcher who uses the word nanoscale, emphasize that this level only include ball-stick and space-filling models as descriptive representation, explanation, and prediction [29].

Another word which is equivalent to the submicroscopic level is structural image [36]. Structural image is indeed not part of the three levels proposed by Johnstone [1]. This term is part of the *logical way of scientific* [36]. However, it involves a structural model to show the relationship of the compound structure to the phenomena and chemical reactions that occur, as well as at the submicroscopic level.

Based on the description above, although the researchers use different terms to refer to the submicroscopic level, it still has broad meaning. The other researchers seem to narrow the meaning of the submicroscopic level and add new terms. For example, Dori & Hameiri [44] adds a process level.

The process level include the processes that occur in chemical reactions [44]. The submicroscopic level only covers particles contained in the material. However, the processes that occur in these particles are included in the process level. Furthermore, the quantum mechanical level also added specifically to cover the electronic structure of atoms, molecules, and solids [46].

Other words used by the researchers relating to this level are very diverse and have been discussed by Gilbert & Treagust [4]. The term submicroscopic is used by them for reasons to avoid ambiguity, as the term microscopic can imply that at this level can be seen through an optical microscope. However, it does not mean that submicroscopic level is an unreal phenomena.

### 3.3. Overview of symbolic level

Representation is useful to represent and communicate [1]. This level includes symbols, reaction equations, stoichiometry, formulas, mathematical manipulation, and graphs [1,27,28]. Then the word symbolic level appears in Johnstone [27] to replace the position of the representation level. The term symbolic level is more widely used by other researchers than the representation level.
Symbolic level can be used to represent macroscopic and submicroscopic level [16,17,5,4,45,44]. Chemical phenomena can be represented by using various media including models, images, algebra, and computational forms such as chemical equations, graphs, reaction mechanisms, and analogies, stoichiometric calculations [17,5]. At submicroscopic level, atoms can be represented by chemical symbols, electric charges with marks, number of particles with subscripts, physical states of matter with letters, chemical reactions with equations [4,6]. In addition, submicroscopic representations can be in the form of reaction mechanisms, Newman and Fischer projections, Lewis structures, graphs, algebraic equations, images of particles in two dimensions [45]. The researchers added the algebra level to separate manipulations using formulas and graphs, such as calculating pH, concentration, from symbolic level [6].

Taber [32] and Talanquer [18] are aware of ambiguities in the use of symbols at the macroscopic and submicroscopic level, such as when symbols are used to indicate certain substance such as methane and CH₄. This is ambiguous, whether the symbol refers to the substance at the macroscopic level or molecule at the submicroscopic level. In line with Bodner [35] who exemplifies the symbol "Na" which can also refer to two levels. Not only that, ambiguity also occurs when using the chemical equation. At the submicroscopic level, the chemical equation can show the processes that occur in chemical reactions, such as which molecules exist before and after the reaction, while at the macroscopic level these equations represent reactants and products. However, Talanquer [18] and Taber [32] solved this problem in a different way.

Talanquer [18] uses the term visualization to replace the symbolic level. Visualization includes static and dynamic visual signs (from symbols to icons) developed to facilitate qualitative and quantitative thinking and communicate about phenomena and model in chemistry. Visualization refers to chemical symbols and formulas, particle drawings, mathematical equations, graphs, animations, simulations, physical models, etc., which are used to visually represent the core components of a theoretical model. Taber [32] considers this ambiguity to be a potential that allows us to shift between macroscopic and submicroscopic level. Therefore, Taber [32] suggests that symbolic level cannot be separated from macroscopic and submicroscopic level, but rather act as a bridge to move between the two levels.

4. Conclusion
Based on the result of this study, the terms macroscopic, submicroscopic, and symbolic are most widely used by researchers in 2009-2020. In addition, we found 15 new terms of three levels of representation within 11 years. Based on the analysis of new terms, the scope of macroscopic, submicroscopic, and symbolic levels become richer and broader. However, sometimes that causes ambiguity and confusion. In line with Gilbert & Treagust, there needs to be an agreement on the level of representation used in chemistry education.

5. References
[1] Johnstone A H, 1982 Macro and micro Chemistry Sch. Sci. Rev. 64, 227 377–379.
[2] Johnstone A H, 1991 Why is science difficult to learn? Things are seldom what they seem J. Comp. Assist. Learn., 7 75-83.
[3] Russell J W Kozma R B Jones T Wykoff J Marx N and Davis J, 1997 Use of simultaneous-synchronized macroscopic, microscopic, and symbolic representations to enhance the teaching and learning of chemical concepts J. Chem. Educ. 74 330–334.
[4] Gilbert J K and Treagust D, 2009 Multiple Representations in Chemical Education.
[5] Treagust D Chittleborough G and Mamiala T, 2003 The role of submicroscopic and symbolic representations in chemical explanations Int. J. Sci. Educ. 25 11 1353–1368.
[6] Nakhleh M B Lafayette W and Krajick J S, 1994 Influence of Levels of Information as Presented by Different Technologies on Students’ Understanding of Acid, Base, and pH Concepts 31 10 1077–1096.
[7] Gabel D L, 1993 Use of the Particle Nature of Matter in Developing Conceptual Understanding 70 3 193–194.
[8] Davidowitz B Chittleborough G and Murray E, 2011 The Impact of Multiple Representation: a useful tool for teaching and learning chemical equations and stoichiometry.
[9] Akaygun S Adadan E and Kelly R, 2019 Capturing Preservice Chemistry Teachers’ Visual Representations of Redox Reactions through Storyboards Isr. J. Chem. 59 6 493–503.
[10] Derman A and Ebenezer J, 2018 The Effect of Multiple Representations of Physical and Chemical Changes on the Development of Primary Pre-service Teachers Cognitive Structures Res. Sci. Educ. 1–27.
[11] Yaman F, 2018 Pre-Service Science Teachers’ Development and Use of Multiple Levels of Representation and Written Arguments in General Chemistry Laboratory Courses Res. Sci. Educ. 1-32.
[12] Roche Allred Z D and Bretz S L, 2019 University chemistry students’ interpretations of multiple representations of the helium atom Chem. Educ. Res. Pract. 20 2 358–368.
[13] Bongers A Northoff G and Flynn A B, 2019 Working with mental models to learn and visualize a new reaction mechanism Chem. Educ. Res. Pract. 20 3 554–569.
[14] Chi S Wang Z Luo M Yang Y and Huang M, 2018 Student progression on chemical symbol representation abilities at different grade levels (Grades 10-12) across gender Chem. Educ. Res. Pract. 19 4 1055–1064.
[15] Sanchez J M P, 2017 Integrated Macro-Micro-Symbolic Approach in Teaching Secondary Chemistry Kimika 28 2 22–29.
[16] Gabel D, 1999 Improving Teaching and Learning through Chemistry Education Research: A Look to the Future J. Chem. Educ. 76, 4.
[17] Chittleborough G D Treagust D F and Mocerino M, 1998 Constraints to the development of first year university chemistry students’ mental models of chemical phenomena Focusing on the Student 43-50.
[18] Talanquer V, 2011 Macro, Submicro, and Symbolic: The many faces of the chemistry “triplet” Int. J. Sci. Edu. 33 2 179-195.
[19] Upahi J E and Ramnarain U, 2019 Representations of chemical phenomena in secondary school chemistry textbooks Chem. Educ. Res. Pract. 20 1 146–159.
[20] Akaygun S, 2018 Visualizations in high school chemistry textbooks used in Turkey ACS Symp. Ser. 1293 2 111–127.
[21] Ye J Lu S and Bi H, 2019 The effects of microcomputer-based laboratories on students macro, micro, and symbolic representations when learning about net ionic reactions Chem. Educ. Res. Pract. 20 1 288–301.
[22] Sweeder R D Herrington D G and Vandenplas J R, 2019 Supporting students’ conceptual understanding of kinetics using screencasts and simulations outside of the classroom Chem. Educ. Res. Pract. 20 4 685–698.
[23] Stieff M, 2019 Improving Learning Outcomes in Secondary Chemistry with Visualization-Supported Inquiry Activities J. Chem. Educ. 96 7 1300-1307
[24] Pavlin J Glazišar S A Slapničar M and Devetak I, 2019 The impact of students’ educational background, interest in learning, formal reasoning and visualisation abilities on gas context-based exercises achievements with submicro-animations Chem. Educ. Res. Pract. 20 3 633–649.
[25] Baptista M Martins I Conceição T and Reis P, 2019 Multiple representations in the development of students’ cognitive structures about the saponification reaction Chem. Educ. Res. Pract. 20 4 760–771.
[26] Gurel D K Eryılmaz A and Mcdermott L C, 2015 A Review and Comparison of Diagnostic Instruments to Identify Students’ Misconceptions in Science Eurasia J. Math. Sci. Tech. Edu. 11 5 989–1008.
[27] Johnstone A H, 1993 The Development of Chemistry Teaching 70 9.
[28] Johnstone A H, 2000 Teaching of Chemistry - Logical or Psychological? Chem. Edu. Res. Pract. 1 1
[29] Lin Y I Son J Y and Hii J A R, 2016 Asymmetric translation between multiple representations in chemistry *Int. J. Sci. Edu.* 38 4 644–662.

[30] Chandrasegaran A L Treagust D F and Mocerino M, 2007 The development of a two-tier multiple-choice diagnostic instrument for evaluating secondary school students’ ability to describe and explain chemical reactions using multiple levels of representation 83 293–307.

[31] Bradley J, 2014 The chemist’s triangle and a general systemic approach to teaching, learning and research in chemistry education *African J. Chem. Educ.* 4 2 64–79.

[32] Taber K S, 2013 Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education *Chem. Educ. Res. Pract.* 14 2 156–168.

[33] Dumon A and Mzoughi-khadhraoui I, 2014 Research and Practice Teaching chemical change modeling to Tunisian students: an “expanded chemistry triplet” for analyzing teachers’ discourse 70–80.

[34] Berg A Ohrayrd D Pettersson A J and Hultén M, 2019 Representational challenges in animated chemistry: self-generated animations as a means to encourage students’ reflections on sub-micro processes in laboratory exercises *Chem. Educ. Res. Pract.* 20 4 710–737.

[35] Bodner G M, 1992 The Fipse lectures: refocusing the general chemistry curriculum why changing the curriculum may not be enough *J. Chem. Educ.* 69 1 186–190.

[36] Barke H-D and Engida T, 2001 Structural chemistry and spatial ability in different cultures *Chem. Educ. Res. Pr.* 2 3 227–239.

[37] Mahaffy P, 2004 The future shape of chemistry education 5 3 229–245.

[38] Mahaffy P, 2006 Moving Chemistry education into 3D: A tetrahedral metaphor for understanding chemistry union carbide award for chemical education 83 1 49–55.

[39] Sjöström J and Talanquer V, 2014 Humanizing chemistry education: From simple contextualization to multifaceted problematization *J. Chem. Educ.* 91 8 1125–1131.

[40] Corradi D M J Elen J and Schraepen B, 2013 Understanding possibilities and limitations of abstract chemical representations for achieving conceptual understanding *Int. J. Sci. Educ.* 36 5 37–41.

[41] Andersson B, 1986 Pupils’ Explanations of Some Aspects of Chemical Reactions 70, 1983 549–563.

[42] Gilbert J K and Treagust D F, 2009 Towards a coherent model for macro, submicro and symbolic representations in chemical education. *Multiple Representations in Chemical Education* 333-350.

[43] Gabel D L Samuel K V and Hunn D, 1987 Understanding the Particulate Nature of Matter *J. Chem. Edu.* 64 8 695–697

[44] Dori Y J and Hameiri M, 2003 Multidimensional analysis system for quantitative chemistry problems: Symbol, macro, micro, and process aspects *J. Res. Sci. Teach.* 40 3 278–302.

[45] Gkitzia V Salta K and Tzougraki C, 2011 Development and application of suitable criteria for the evaluation of chemical representations in school textbooks *Chem. Educ. Res. Pract.* 12 1 5–14.

[46] Dangur V Avargil S Peskin U and Dori Y J, 2014 Learning quantum chemistry via a visual-conceptual approach: Students’ bidirectional textual and visual understanding *Chem. Educ. Res. Pract.* 15 3 297–310.