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Demonstrating chemistry phenomena and stimulating back-and-forth thinking of students between phenomena, concepts, and various representations and visualizations

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Abstract
Johnstone's "chemistry triangle" comprises three levels of processing to describe and explain chemical phenomena: Macro-, Micro-, and Symbolic-level. Experienced chemists can easily switch between the different levels, but learners often struggle to do so. Students have to learn to think back-and-forth between phenomena and theory and switch between the three levels of description and explanation of phenomena. This article describes the relationship between hands-on and minds-on approaches to learning chemistry concepts through teacher demonstrations. We provide guidance and a strategy to facilitate smooth switching between the different levels. In Section 1 we introduce "meaning-making" through Thinking Back-and-Forth (TBF) between the Domain of Observables (phenomena, objects, and observations) and the Domain of Ideas (concepts, theories, and models). In Section 2, the back-and-forth thinking model is expanded to incorporate the various levels of processing as outlined in Johnstone's "Chemistry Triangle". Finally, in Section 3, we conclude with some strategies for visualizing the micro level. To illustrate the back-and-forth thinking between phenomena, concepts, and visualizations we used the example of the reaction between a copper(II)nitrate solution and iron nail/ steel wool.

Keywords: hands-on/minds-on, connecting phenomena with concepts, visualizations, representations; Thinking Back-and-Forth, Chemistry Triangle

1 MEANING-MAKING THROUGH THINKING BACK-AND-FORTH (TBF)

In a lesson on what it takes to germinate seeds towards the end of grade 1, age 6 or 7, the following discussion unfolded after children had studied a collection of seeds on their table [1]:

Rosa: *If you put the seed in the pot and add some water then it will start to grow*. A classmate: *Then the roots can drink*. Teacher: *But the seed doesn't have roots, does it?* Another child: *Those will come*. And then Jesse: *It's the same as with humans. Food for people is like water for a flower. If I eat then I grow. If the flower drinks, then it grows*. Another child: *but where is the mouth?* Jesse: *the roots drink for the plant.*

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In this piece of meaning-making, we see children formulating their ideas using concepts such as seeds, roots, and even an analogy between people and plants. The brain is in full swing catching phenomena in language and concepts. This happens also in young learners; it is a natural process. People do this as soon as they use language. With their language, they go back and forth between phenomena and concepts, they reason with phenomena and concepts, which is the core of natural science.

In science, phenomena are central. We try to describe and understand them, first with everyday language, then with subject concepts and models. As we do so, new questions arise, we go back to the phenomenon and usually see more than the first time. New observations in turn raise new questions, we develop hypotheses and theories, which we can test by going back to the phenomenon. And so our understanding of the phenomenon develops in a spiral of observing, reflecting/questioning, and again observing and experimenting, in short, TBF between phenomena and theory.

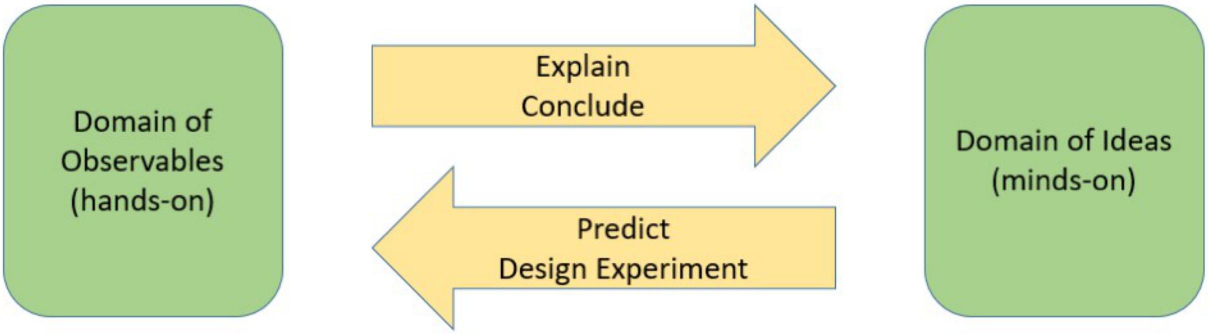

Figure 1. The Domain of Observables (phenomena, observations, measurements) on one side, and the Domain of Ideas (concepts, theories, and models) on the other side, and the Thinking Back-and-Forth (TBF) operations that bridge them [3].

To define TBF, we distinguish between the Domain of Observables ('hands-on') and the Domain of Ideas ('minds-on') [2,3]. A Thinking Back-and-Forth activity is any activity in which the learner (or teacher) uses and links a hands-on aspect and a minds-on aspect in one argument, see Figure 1 [4].

On the left is the world of observables in which we observe, measure, and perform our experiments, and on the right is the world of ideas (theory) in which we reason with concepts, theories, and models. The connections are the TBF processes of explaining, concluding, asking new questions, predicting outcomes, and designing experiments. In explaining and concluding, we move from the Domain of Observables to the Domain of Ideas. From these, new questions arise that send us back to the phenomena. In predicting, we use models to predict phenomena and measurements, and we design experiments to test those predictions. In the tension between observation (hands-on) and explanation (minds-on), wonder and curiosity arise.

For instance, the observations of simply adding a vitamin C effervescent tablet in water can already lead to many questions. Questions that may arise: What kind of bubbles are there? Why is my tablet floating? What happens if I increase the temperature of the water?

The pedagogical challenge: building bridges between phenomena and concepts

During hands-on activities including demonstrations, students pay attention mainly to actions and phenomena, and much less to subject concepts and theory. From the student's perspective, there appears to be a gap between the Domain of Observables, and the Domain of Ideas. That gap is explicitly addressed by the TBF framework, which allows teachers to deliberate carefully which TBF activity is a valuable addition to any classroom demonstration and design the demonstration accordingly. In doing so, existing demonstrations can be improved in tangible steps, such that they bridge that gap [5]. Teachers react appreciatively to the possibilities the TBF framework provides in this respect [4]. In addition to focusing student attention on TBF, teachers should take care to avoid any hands-on distractions to achieve minds-on learning goals [6]. In a teacher demonstration, the “noise” from irrelevant side effects is much less than in a student practical, since the teacher is more apt at hands-on aspects than the students and the teacher can emphasize any important aspects. The challenge then becomes getting the students to do the TBF.

In PEOE (Predict-Explain-Observe-Explain) demonstrations, TBF is integrated in the PEOE procedure (the P and the E’s). Students in a demonstration are asked to predict individually and on paper with arguments (Predict-Explain) followed by a short(!) and matter-of-fact think-and-share exchange in pairs or in a classroom teaching-learning discussion. Then follow experiment and observation or measurement. Then again individually and on paper the observation plus explanation by the student, again followed by group or classroom exchange. Incorrect explanations derived from “alternative” theories or misconceptions can also represent TBF, e.g. a student explaining the bubbles (observation) when boiling water as air that bubbles upwards (concepts) instead of water vapor. PEOE demonstrations have been well described by White and Gunstone [7] and have since been popular in both classroom practice and research with encouraging results [8].

Of course, there are many demonstrations where learners cannot simply predict results and the PEOE model does not fit. Nevertheless, there are possibilities to engage students in TBF by getting them involved in explaining, concluding, and designing a follow-up experiment, if necessary step-by-step. See, for example, the TBF table below. Which can be used during a practical session to stimulate and pre-structure TBF.

The TBF Table

We take as an example the demonstration test of the Redox reaction between an iron nail or steel wool and a solution of copper(II)nitrate. Start with a light blue solution of copper(II)nitrate and a grey solid nail or a small piece of steel wool. After a few minutes, two things stand out:

1- The nail/steel wool turns brown on the outside and
2- The solution turns from light blue to green.

One can create a TBF table using this reaction. The following text describes the creation of a TBF table containing four columns: “What do you see?”, “What do you think?”, “What happens at the micro level?”, and “To symbol level.”. In order to reach the domain of ideas, an empty Table 1 can be filled in by students during a practical session to stimulate back-and-forth thinking. This table can be extended with the microlevel and the symbol level as can be seen in Table 2 and Table 3a/b. In a teacher demonstration, the teacher can fill in the table collectively in a teaching discussion or let students fill in parts individually during the demonstration, which enhances student engagement. An empty Table 3a and 3b with the four columns, can be seen as a blueprint for chemical demonstrations to teach concepts.

Table 1: Example of a TBF table Redox reaction between iron nail or steel wool and solution of copper(II)nitrate.

What do you see?	What do you think?
The blue color from the solution disappears.	The substance causing the blue color disappears. Which substance causes the blue color?
A red/brown layer forms on the nail/steel wool.	Iron is coated with another substance. What substance would this be given the red/brown color? It can't be rust because rust formation takes much longer (months). Could it be copper? How can we confirm this?
The solution turns green.	A substance is formed that causes the green color. Could it be Fe^{2+}?

The teacher could add a third column with “What is my follow-up experiment?” to link back to the phenomena, or a column of micro-level statements (molecules/atoms), see Section 2. Follow-up experiments could be investigations into the influence of concentration and degree of partitioning on reaction rates (nail versus steel wool). Similar TBF tables are useful both in the preparation of demonstrations (to be filled in by teacher), and in the classroom (to be filled in in classroom discussion or by students individually or in small groups).

How do we bring this TBF into the pedagogy of demonstrations?

We can do so in a step-by-step preparation for a demonstration:

1. Make a list of phenomena observable in the demo. What phenomena are they? Think about which phenomena you want to emphasize. The primary concern is the color change of both the metal and the solution. Usually, there are also observable aspects that are NOT relevant to the main purpose of the demonstration. For example, when using steel wool, "pieces" of the steel wool fall off. Or "protrusions" appear on the nail.
2. List the concepts associated with the phenomena. Such concepts are ions, atoms, electrons, and the exchange of electrons. Distinguish between the main concepts and other concepts that you initially avoid to prevent confusion. You want to avoid discussing a concept like rust in-depth with students at this moment.
3. Devise a pedagogical roadmap for the demonstration. Sometimes it is wise to do a global introduction to the phenomena first and then more precise observations. For this experiment you look directly at the color changes, later you could ask questions about how the reaction rate might slow down or speed up. What can we do to increase or decrease the rate of reaction?
4. What are your introductory remarks to get students ready to integrate the experience well with prior knowledge later in the demo? Don't give away the results of the demo in the introduction. Do draw students' attention to the phenomena you consider important (viewing guide).
5. Make a table as above with "I see that", "I think that", and possibly a third column with questions or with concepts at micro level (atoms/ions/molecules). During the demonstration, this table is first presented blank and then filled in by the students or by the teacher in dialogue with the students, see Section 2.

In short

In practical activities, it is important to think explicitly back-and-forth between phenomena, objects, and observations (in the Domain of Observables) and concepts, models, and theories (in the Domain of Ideas). Within chemistry, during minds-on, we also engage in thinking back-and-forth between Johnstone's different levels [8,9]. We will discuss this further in section 2.

2 TOWARDS AN EXPLANATION: FROM PHENOMENA TO MICRO (EXPLAIN)

In the previous section, we looked from the macroscopic perspective using TBF to induce thinking. In chemistry, macro-micro thinking is the foundation of understanding. When we want to explain the phenomenon using the concepts, we need the micro level and symbol level in chemistry.

Johnstone's [9,10] "chemistry triangle" comprises three levels of processing to describe and explain chemical phenomena:

1. Macro: description of phenomena with concepts such as temperature, pressure, mass, volume, color, energy;
2. The (sub-)micro or invisible level: the atoms, ions and molecules;
3. The symbolic level: the way chemical processes and objects are represented through symbols, formulas and reaction equations [11].

When the different processing levels are connected, stronger networks in thinking are created, resulting in better learning outcomes in learners [12]. Johnstone [13] argues that experienced chemists can switch between the different processing levels without difficulty, but learners have great difficulty doing so. Students have to learn to think back-and-forth between phenomena and theory and switch between the three levels of description and explanation of phenomena. This is illustrated in Figure 2.

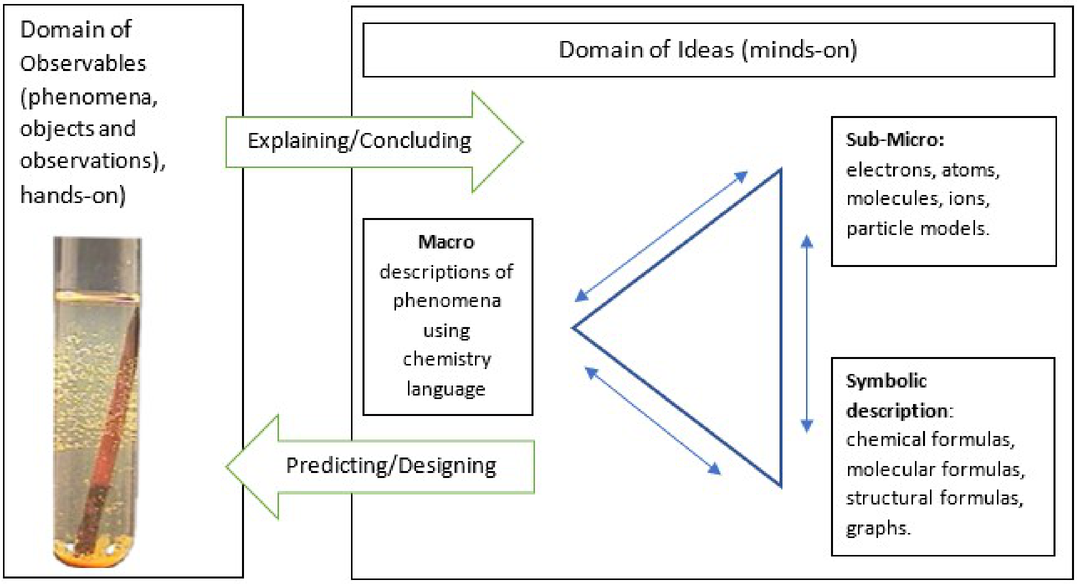

Figure 2. On the left is the Domain of Observables (phenomena, objects, and observations), on the right is the Domain of Ideas (concepts, theory, and models), and within that the chemical triangle of Johnstone.

A thinking back-and-forth activity is an activity in which the learner links elements of the Domain of Observables to the Domain of Ideas. The teacher should explicitly pay attention to the differences between macro and micro. For example, an iron nail (observable, macro-level) consists of atoms (micro-level) and has the chemical formula "Fe" (symbolic-level). A blue solution of the salt copper(II) nitrate in water (observable, macro-level) consists of separate ions (micro-level) and the notation of the solution is "Cu^{2+}(aq) and $2NO_3^{2-}$(aq)". The ultimate learning goal is that students can think back-and-forth between phenomenon and theory, and switch between the symbol level and the symbolic description as structural formulas, reaction equations, and graphs within the Domain of Ideas. Explaining and predicting form the bridge between interpreting observations and explaining at the micro (particle) level. The teacher can be a role model by explicitly naming the macro-, micro-, and symbolic levels when explaining, and explicitly going back-and-forth between the levels.

Extension of the TBF table: From phenomenon to reaction equation

The experiment of the reaction between iron and copper(II) ions aims to teach students to write down the setting up of half-reactions, and from the half-reactions to formulate the total reaction equation. In the Domain of Observables, we describe this as the browning of the nail, and discoloration of the solution from blue to greenish. At the sub-micro level, we think of Fe and Cu atoms, Fe^{2+} ions, $Cu^{2+,}$ and NO_3^- ions and we imagine a rearrangement of particles. At the symbolic level, there are the reaction equation and structural formulas. We can ask questions and switch between the different levels. So the teacher can explain macro-observation at the micro level and represent the observables at the symbolic level in a balanced chemical reaction equation.

We could extend the previous Table 1 with "I see that", "I think that", by adding a third column with "What happens at the micro level" (atoms/molecules). This will serve as a starting point for explaining the observations. During the demonstration, Table 2 is initially presented blank and then filled in by the students or by the teacher in dialogue with the students. See Table 2 for this. Depending on your learning objective, you can have all parts explained or focus only on what is relevant to your learning objective.

Table 2: Example of a TBF table Redox reaction between iron nail/ steel wool and solution of copper(II)nitrate, with the column "What happens at micro level".

What do you see?	What do you think?	What happens at the micro level?
The blue color from the solution disappears.	The substance causing the blue color disappears. Which substance causes the blue color?	Solutions contain ions or molecular substances. We started with a salt solution (copper(II)nitrate) so ions must be present. According to a table of properties of ions, copper(II) ions Cu^{2+} (aq) give the blue color in this solution.
A red/brown layer forms on the nail/steel wool	Iron is coated with another substance. What substance would this be given the red/brown color? It can't be rust because rust formation takes much longer (months). Could it be copper?	Copper and nitrate ions are present in the solution. In addition, only Fe(s) is present as the starting substance. The red/brown color could indicate Cu(s). The copper may have formed from Cu^{2+} ions. According to a table of properties of ions, iron ions do not give a red/brown color in solution.
The solution turns green.	A substance is formed that causes the green color. Which substance?	Solutions contain ions or molecular substances. A solution with Fe^{2+} (aq) will appear greenish.

From phenomena to half-reactions to reaction equations.

As a strategy for learning to formulate half-reactions and overall reactions from observations, the teacher can go through the steps below with the students. The step-by-step reasoning is shown below, the teacher can make his/her adaptations. Table 2 is extended with the "symbol level" column to arrive at half-reactions from observations and eventually the overall reaction.

The teacher shows the nail or steel wool and the copper(II)nitrate solution and asks students to note the different particles present at the beginning. Students write down the particles as: Cu^{2+} (aq), NO_3^- (aq), H_2O (l), Fe (s). The copper(II)nitrate solution is added to the iron. The steel wool turns brown on the outside and the solution turns from light blue to green.

What happens during the experiment?

Observation 1: The blue color of the solution disappears.

Observation 2: The nail/steel wool becomes coated with a red/brown substance. A student could think that this red/brown layer is rust, and it is good to point out in advance that this is not the case (as rust formation requires much more time). Since only iron metal atoms and copper ions are present, and iron is a grey metal, it is obvious that the brown metal must be copper. Where does metallic copper come from? The only copper particle present is Cu^{2+} (aq). This forms Cu(s).

Prepare the half reaction together: Cu^{2+} (aq) $\rightarrow$ Cu (s).

Balance this half reaction according to:

Step 1: write down the correct particles (particle balance)
Step 2: balance the total charge on both sides of the arrow (charge balance)

Balancing the charge is possible only if a minus charge is also involved: electrons e^- are needed.

Cu^{2+} (aq) + 2 e^- $\rightarrow$ Cu (s)

Cu^{2+} (aq) is an oxidizing agent (oxidant), the copper ions accept electrons, so electrons enter the equation to the left of the arrow. We call this the half-reaction of the oxidizing agent.

The half-reaction of the copper ions is entered in column 4 of Table 3a.

Observation 3: A green color develops, while the blue color of the solution disappears. This may be because Fe^{2+} ions are formed. Where do Fe^{2+} ions come from? The only iron particle is Fe(s). This forms Fe^{2+} ions.

Write the reaction equation: Fe (s) forms Fe^{2+} (aq), but the half-reaction has to be balanced for charge.

Fe(s) $\rightarrow$ Fe^{2+} (aq) + 2 e^-

Table 3a: Example back-and-forth thinking table Redox reaction between iron nail and solution of copper(II)nitrate, with column “symbol level”.

What do you see?	What do you think?	What happens at the micro level?	To symbol level.
The blue color from the solution disappears.	The substance causing the blue color disappears. Which substance causes the blue color?	Solutions contain ions or molecular substances. We started with just a salt solution (copper(II)nitrate) so ions must be present. So copper(II) ions Cu^{2+}(aq) give the blue color in this solution. Something happens to the copper ions.	Write the half reactions. From the particle balance (column III) it follows: Cu^{2+}(aq) → Cu(s). Balancing the charges is possible only if negative charge is also involved: electrons e^- are needed. Cu^{2+} (aq) + $2e^-$ → Cu (s)
A red/ brown layer forms on the nail/ steel wool	Iron is coated with another substance. What substance would this be given the red/brown color? It can't be rust because rust formation takes much longer (months).	Copper and nitrate ions are present in the solution. In addition, only Fe(s) is present as the starting substance. Cu(s) is red/brown. The copper metal Cu may have formed from Cu^{2+} ions. Iron ions do not give a red/brown color in solution.	
The solution turns green.	A substance is formed that causes the green color.	Solutions contain ions or molecular substances. Iron(II) ions Fe^{2+} (aq) give a green color.	Fe (s) forms Fe^{2+}(aq) this is only possible if negative charges are donated: Fe (s) → Fe^{2+}(aq) + $2e^-$

Electrons never appear as - e^- on the left side of the half-reaction but are formed as + e^- on the right.

Fe(s) is a reducing agent (reductant), the iron atoms donate electrons, so electrons are placed on the right of the arrow. We call this the reducing half-reaction.

There are now two half-reactions: one in which electrons are donated (the reductant, Fe) and one in which electrons are accepted (the oxidant, Cu^{2+}).

Ask students how to combine these reactions into an overall reaction that contains no electrons.
These two half-reactions are then added up. Here, the number of electrons donated by the reductant must equal the number of electrons accepted by the oxidant.

Cu^{2+} (aq) + 2 e^- → Cu (s) x1
Fe (s) → Fe^{2+} (aq) + 2 e^- x1

Cu^{2+} (aq) + 2 e^- + Fe (s) → Cu (s) + Fe^{2+} (aq) + 2 e^-
Cu^{2+} (aq) + Fe (s) → Cu (s) + Fe^{2+} (aq)

Attention: for clarity, have the arrows be placed in the same position, and have electrons explicitly crossed away left and right.

The table below can be seen as an addition/completion to the earlier Table 3a.

Table 3b: Example back-and-Forth Thinking Table Redox reaction between iron nail and solution of copper(II)nitrate, completed with the final objective: the overall reaction at the symbolic level.

What do you see?	What do you think?	What happens at the micro level?	To symbol level.
The solution turns from blue to green, and a red/brown metal is formed.	A redox reaction occurs.	Copper ions react with solid iron atoms.	You can now formulate the overall reaction: Cu^{2+} (aq) + Fe (s) → Cu (s) + Fe^{2+} (aq)

In short

The teacher can explain chemical phenomena by explicitly thinking back-and-forth between the Domain of Observables (phenomena, objects and observations) and Ideas, where the Domain of Ideas in chemistry can be subdivided into the different levels of Johnstone. This TBF and the switching between the Johnstone levels is very difficult for students. To avoid or confront misconceptions, micro-level visualizations can be a very effective tool.

3 MICRO-LEVEL VISUALIZATION

When concepts are difficult for learners, attention can be paid to visualizing phenomena at the (sub-) microscopic level. This can produce a significant positive learning effect in students [14]. The teacher can pay attention to the micro level using different types of models each with its specific advantages and disadvantages.

Simple drawings can be helpful. Tasker and Dalton [15] have developed an instructional strategy (VisChem), which provides a way for students to relate observations(macro) to micro- and symbolic-level through a so-called storyboard. This storyboard lets learners visualize their mental model at the micro-level using drawings and accompanying texts [15]. This quickly reveals any misconceptions students may have, and students can then identify and correct their misconceptions after showing them a visualization or having a class discussion. In the case of the redox reaction between the iron nail and the solution of copper(II)nitrate, the microlevel can be represented as shown in Figure 3. Note the change in color of the solution and the formation of a layer of Cu-atoms on the surface of the iron nail. Of course, this representation is simplified: the copper layer will not be mono-atomic.

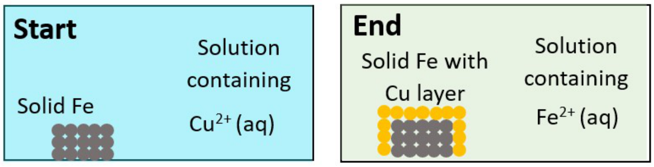

Figure 4: Microlevel representation of the redox reaction between the iron nail and the solution of copper(II)nitrate at the start and the end of the experiment.

For organic compounds, we use structural formulas, often in the form of a 2-3 dimension projection, which show the bonds and are easy to draw. There are Ball-and-Stick models, based on the atomic building blocks with which we also pay attention to the spatial structures. The molecule building box can generally only be used at school and has limitations in the amount of building material available. There is also software like Avogadro or ChemSketch, available for free download, where molecules can be rotated. But sometimes you also want to show the movements of molecules among themselves and animations or videos are more desirable. Examples of visualizations that have proven their added value are Avogadro/ PhET / VisChem/ AACT (American Association of Chemistry Teachers). A hyperlink to the website for each program is provided in the appendix. Many videos can be found on the internet, however, it is very important to check all materials on chemical inconsistencies or mistakes.

The video created for Show*de*Chemie [16] called "Show*de*Chemie Ijzer in oplossing koper(II)nitraat" (https://youtu.be/r-fsmqQklFc) shows not only what happens at the macro level but also at the micro level. The video is a compilation of several fragments from AACT.

In short

Science is about thinking back-and-forth between the Domain of the Observables and the Domain of Ideas. Phenomena are explained through theoretical models, from these models new phenomena can be predicted. In chemistry, within the Domain of Ideas, students learn to switch between the micro and symbolic levels. In this process, we use various representations such as reaction equations, structural formulas, visualizations, and simulations. Visualization of the microlevel enhances students understanding. The more easily students can switch between all these phenomena, representations and visualizations, the more understanding they will gain. For another interesting discussion about implications and recommendations for chemistry instruction and research at secondary and undergraduate levels see Wu and Yezierski [17].

Appendix:

Avogadro.

To understand, the spatial construction of molecules, you can use the free molecular drawing software Avogadro. With this software, not only molecules but also interactions between molecules, based on hydrogen bonds, can be represented. The necessary software, freeware, can be downloaded from the site https://avogadro.cc/

ChemSketch

ChemSketch is a molecular drawing software, ideal for chemists to create accurate chemical structures and diagrams. It allows users to draw, modify, and visualize chemical structures, making it an essential tool for molecular modeling and chemical documentation. Additionally, ChemSketch facilitates the generation of 3D molecular models, aiding in the analysis of molecular geometry and spatial arrangements. The necessary software, freeware, can be downloaded from the site https://www.acdlabs.com/resources/free-chemistry-software-apps/chemsketch-freeware/

PhET Interactive Simulations

For animations of a large number of subjects, the PhET Interactive Simulations site from the University of Colorado Boulder is a good place to look. https://phet.colorado.edu/nl/

Visualizing Chemistry (VisChem)

Visualizing Chemistry, in short VisChem, is another good site for visualizations at the molecular level. Roy Tasker and his team have created animations, videos, and supplementary materials at the molecular level. A pdf is available that contains all the links to videos. But also an Excel file with the links to the YouTube videos. What is clearly visible is that in most animations, the three levels (macro-micro symbol), are named and visible. http://vischem.com.au/

AACT

AACT, the American Association of Chemistry Teachers, has compiled a Classroom Resource Library, with more than 1000 items from dedicated teachers and carefully organized by chemistry topics within AP units, high school, middle school, and elementary school. Each topic includes different kinds of multimedia resources among other animations and simulations.

Registration is required to access materials: https://teachchemistry.org/classroom-resourcesg).

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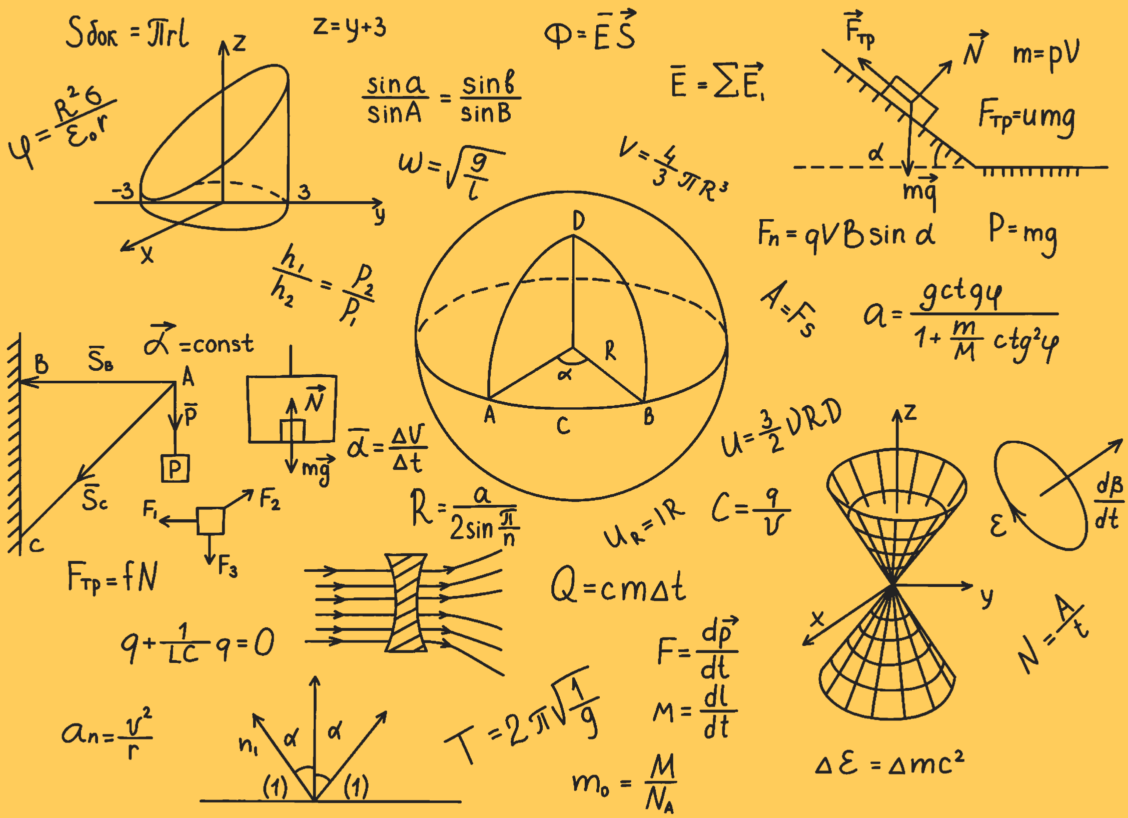

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